

## Simultaneous FUV and NUV observations of T Tauri stars with UVIT/AstroSat: probing accretion process in young stars

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### ABSTRACT

We present results from simultaneous FUV and NUV observations of T-Tauri stars (TTSs) in the Taurus molecular cloud with UVIT/AstroSat. This is the very first UVIT study of TTSs. From the spectral energy distribution of TTSs from FUV to IR, we show that classical TTSs (CTTSs) emit significantly higher UV excess compared to weak-line TTSs (WTTSs). The equivalent black-body temperatures corresponding to the UV excess in CTTSs ( $> 10^4$  K) are also found to be relatively higher than that in WTTSs ( $< 8500$  K). From the UV excess, we have re-classified two WTTSs (BS Tau, V836 Tau) as CTTSs, which has been supported by the follow-up optical spectroscopic study using the Himalayan Chandra Telescope (HCT), showing strong H $\alpha$  line emission. We find that CTTS show strong excess emission in both FUV ( $> 10^7$ ) and NUV ( $> 10^3$ ) bands, while WTTS show strong excess only in the FUV ( $\lesssim 10^5$ ), suggesting that excess emission in NUV can be used as a tool to classify the TTSs. We also find a linear correlation between UV luminosity (a primary indicator of mass accretion) and H $\alpha$  luminosity (a secondary indicator of mass accretion) with a slope of  $1.21 \pm 0.17$  and intercept of  $2.18 \pm 0.56$ .

**Keywords:** stars: pre-main sequence; ultraviolet: stars; protoplanetary disks

### 1. INTRODUCTION

T Tauri stars (TTS) are low-mass pre-main-sequence (PMS) stars, generally categorized into Classical TTS (CTTS) and Weak-line TTS (WTTS) based on their strength of H $\alpha$  emission (Alcala et al. 1993; Duvert et al. 2000; Gras-Valázquez & Ray 2005). CTTS show strong and broad H $\alpha$  emission indicating active ongoing accretion from the circumstellar disk onto the central star, while WTTS show weak and narrow H $\alpha$  emission, suggesting weak or no accretion (Herbig & Bell 1988; Martín 1998; White & Basri 2003; Barado y Navascués & Martín 2003).

Circumstellar disks form during the process of star formation due to the conservation of angular momentum and in their short lifetimes ( $\sim$  a few Myrs) aid both star and planet

formation. Material from the disk around the CTTS is channelled onto the stars along the strong magnetic field lines and generates accretion shocks on the stellar surface, producing hot spots (Hartmann et al. 2016, and references therein). The kinetic energy of the freely in-falling material is dissipated in these accretion shocks. Behind these shocks, the energy is converted into radiation which flows back out through the shocks and into the in-falling material. Most of the escaping radiation peaks in the ultraviolet with estimated black body equivalent temperatures of  $\sim 10^4$  K (Calvet & Gullbring 1998). Thus, accreting stars are characterized by strong UV excesses (Gorti & Hollenbach 2009). The cool and dusty layers of the disk absorb this radiation and re-emit at the infrared wavelengths. Hence, the accretion process causes the release of excess energy not only in the UV but also in the IR regions of the spectral energy distribution of a CTTS. The UV emissions mainly originate from the hot spots produced by accretion shocks, while near-IR (NIR) and mid-IR emissions come from smaller disk radii while far-IR comes from

the midplane of the outer disk. As the disk disperses, the SED gradually shows less excess in the IR region (Lada 1987). Non-accreting WTTS also shows excess in UV due to chromospheric activity and significantly reduced excess in IR due to the presence of a smaller or depleted disk (Ingleby et al. 2011; Schneider et al. 2020).

FUV photons from the star play an important role in heating disk gas and can drive massive thermal winds that eventually deplete disk material. Recent research suggests that FUV-aided dispersal and heating can have consequences for angular momentum transport through magneto-centrifugal winds (e.g., Bai et al. (2016)) and the formation of planetesimals (Carrera et al. 2017). FUV photons significantly affect disk chemistry—the differences in the molecule content of low-mass TTS and intermediate-mass Herbig stars is believed to be due to the stronger UV flux from the latter (Pascucci et al. 2014). This could have implications for the composition of planetesimals and planets that eventually form in these disks. Even after the disk is dispersed, the bright FUV flux from WTTS could impact the evolution of proto-planets and potentially strip their atmospheres (Owen & Wu 2016). Characterizing FUV emission from T Tauri stars and understanding the time evolution of the spectrum is critical to understanding disk evolution (Gorti & Hollenbach 2009), and more fundamentally, the accretion process itself.

There have been several UV spectral surveys of TTS by the IUE (Valenti et al. 2003) and the STIS instruments on the HST (Yang et al. 2012). While these studies have yielded valuable information on the FUV spectrum, most of the measurements of the FUV and NUV excesses are not simultaneous. It is thought that the NUV and the FUV flux originate from different regions of the accretion flow. The NUV Balmer continuum arises from the dense pre-shock region of the accretion column and the FUV most likely arises near the hot spot (Ulrich 1976; Calvet & Gullbring 1998; Ingleby et al. 2013; Hartmann et al. 2016); this makes contemporaneous observations of both bands necessary for understanding the link between the NUV and the FUV emitting regions and the nature of the accretion process (France et al. 2014). UVIT on AstroSat, with its capability of accurate and simultaneous multi-band UV photometry, is the ideal instrument for probing the FUV-emitting regions around young stars. The use of multiple filters, three filters each in the FUV ( $\lambda_{eff} = 1481 \text{ \AA}$ ,  $1541 \text{ \AA}$  &  $1608 \text{ \AA}$ ) and NUV ( $\lambda_{eff} = 2447 \text{ \AA}$ ,  $2632 \text{ \AA}$  &  $2792 \text{ \AA}$ ) bands, will give us three-wavelength points allowing us to better reconstruct the flux distribution across FUV and NUV regions.

In this paper, we present simultaneous multi-band observations in FUV and NUV bands of T-Tauri Stars in the Taurus Molecular Cloud. We have modelled the UV flux with a black-body spectrum and have determined the corresponding temperature and luminosity. For CTTS, the black-body luminosity will provide a direct measure of accretion luminosity. We investigated if there is any significant difference in the black-body temperatures between CTTS and WTTS, i.e., between peak temperature for the emission due to accre-

tion and emission due to chromospheric activity. We have also revisited the classification scheme based on the amount of UV excess emitted by TTS over photospheric emission and the strength of the  $H\alpha$  emission. We also search for correlations between UV luminosity and other commonly used accretion/disk tracers such as  $H\alpha$  luminosity and IR excess emission.

The remaining sections of this paper are arranged as follows. In Sect. 2, we discuss the UVIT data, the follow-up optical spectroscopic observation from ground-based telescopes, and SED analysis of T-Tauri stars. In Sect. 3, we present our results and discuss them. In the Sect. 4, we summarize our results from this study and their implications.

## 2. DATA SELECTION AND ANALYSIS

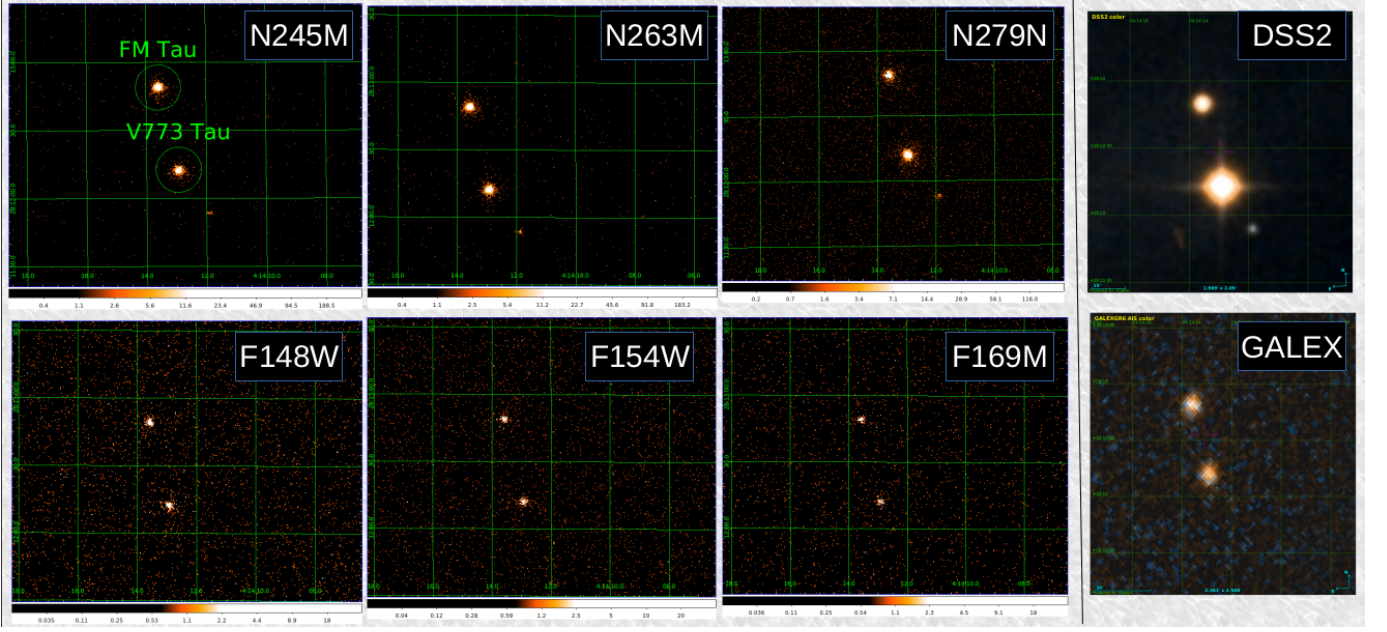
### 2.1. Photometry: UVIT observations

Four TTS fields in the Taurus Molecular Cloud (TMC) were observed with UVIT onboard AstroSat (proposal id: A04-210; PI: Annapurni Subramaniam). Each of these fields has a diameter of  $\sim 28'$  and were centered on the following TTS: FM Tau, V836 Tau, BS Tau, and HD283782. All the observations were carried out using three FUV and three NUV filters in January of 2018. The names of the FUV and NUV filters and corresponding exposure times for all targets are listed in Table 1. FM Tau is observed in the narrow band filter, N279N, centered at the Mg-II line, while other TTSs are observed in the N242W wide band, keeping the other two medium bands (N245M and N263M) as common filters for all the targets.

The observations were completed in multiple orbits. We applied corrections for spacecraft drift, flat-field, and distortion using the software CCDLAB (Postma & Leahy 2017) and created images for each orbit. Then, the orbit-wise images were co-aligned and combined to generate final science-ready images in each filter. Astrometry was also performed using CCDLAB by comparing the Gaia-DR2 source catalogue. The science-ready images were created for an area of  $4K \times 4K$  in size with a scale of  $0.''416/\text{pixel}$ . The details about the telescope and the instruments are available in Subramaniam et al. (2016); Tandon et al. (2017a) and the instrument calibration can be found in Tandon et al. (2017b, 2020).

We used the DAOPHOT tasks and packages in the Image Reduction and Analysis Facility (IRAF)<sup>1</sup> software (Stetson 1987) to carry out the photometry. To detect the sources, we used a threshold of six times the background variation. We performed aperture photometry on the detected stars. We applied saturation corrections to aperture magnitudes and calculated the final magnitudes of the detected stars in the AB magnitude system in the corresponding bands by adding zero-point magnitudes. The values of zero-point magnitudes

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation



**Figure 1.** Multi-bands FUV and NUV images of FM Tau and V773 Tau are presented here. The names of the different filters are marked here. DSS2 and GALEX images are also presented for comparison.

for the corresponding filters are taken from Tandon et al. (2020).

Given the large field of view (FOV) of UVIT, it is possible that other TTS can also be present in the same FOV. To detect these serendipitous TTS, we cataloged UVIT-detected stars in the various fields and cross-matched them with the Gaia and UV catalogs of the TMC members from Esplin & Luhman (2019), Nayak et al. (2023) and Inés Gómez de Castro et al. (2023) to search for more UV counterparts to TMC members. With UVIT we were able to detect seven more TTS in the field of FM Tau. These are V773 Tau, CW Tau, FN Tau, FO Tau, CIDA 1, Anon 1, and 2MASS J04141188+2811535. While three of the targets (V773 Tau, CW Tau, FN Tau) were detected in both NUV and FUV, four of the TTs (FO Tau, CIDA 1, Anon 1, and 2MASS J04141188+2811535; hereafter J0414) were only detected in NUV. No additional TTSs were detected in the FOV of BS Tau, V836 Tau and HD 283782. The UVIT magnitudes in various filters of all the 11 detected TTSs and their coordinates are given in Table 1.

In Figure 1, we show UVIT FUV and NUV images of FM Tau and V773 Tau in different filters. DSS2 and GALEX images of these three sources are also presented in the right most panels of Figure 1 for comparison. The images clearly show UVIT has better resolution ( $\sim 1''.4$ ) than the GALEX. Figure 1 also shows that V773 Tau is brighter than FM Tau in optical (DSS2); however, they appear of similar brightness in UV and their UV magnitudes listed in Table 1 also convey the same, indicating that FM Tau exhibits strong excess emission in UV. We discuss the excess UV emissions from all the TTs in detail in the latter sections.

## 2.2. Spectroscopy: HCT observation

We obtained low-resolution optical spectroscopic of all 11 TTs. As the optical spectroscopy and UV observations are not simultaneous, it is necessary to obtain multi-epoch spectra of these sources, which will allow us to identify if there is any variability in the  $H\alpha$  emission, i.e. variability in the accretion rate. We observed five of our targets with Himalayan Faint Object Spectrograph Camera (HFOSC)<sup>2</sup> mounted on the 2 m Himalayan Chandra Telescope (HCT). We also searched the LAMOST database and found optical spectra of eight out of eleven of our targets. In Table 2, we have listed the names of the sources, from where the spectra are obtained, and observation dates of different epochs for each source. Except for Anon1 and HD283782, we obtain multi-epoch observations of all the other sources.

For the HCT spectra, the wavelength range was covered using Grism 8 (5500–9000Å) with an effective resolving power of  $\sim 1050$ . Flat frames have been taken before each on-target observation, while bias frames have been taken both before and after the on-target observation. The FeNe lamp spectra were also obtained after each on-target observation for wavelength calibration. The HCT spectra were reduced in a standard procedure after bias subtraction and flat-field correction using the standard tasks in the IRAF software and the HCT pipeline HAPLI (Narang et al. 2023). Then wavelength calibration is performed on extracted spectra for further analysis.

<sup>2</sup> Further details of the instruments and telescopes are available at <http://www.iap.res.in/iao/hfosc.html>

**Table 1.** The list of 11 TTS candidates observed with the UVIT.

TTS	RA	Dec	Filters	exposure	magnitude	Filters	exposure	magnitude	Object
Name	hms	dms	(NUV)	Time (sec)		(FUV)	Time (sec)		(Type)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
FM Tau	4 14 13.6	28 12 49.2	N245M	1221	17.46	F148W	1208	19.98	CTTS
			N263M	958	16.98	F154W	1207	19.75	
			N279N	1211	16.56	F169M	945	19.62	
V773 Tau*	4 14 13.6	28 12 49.2	N245M	1221	17.80	F148W	1208	20.65	WTTS
			N263M	958	16.92	F154W	1207	19.94	
			N279N	1211	15.95	F169M	945	20.0	
CW Tau*	04 14 17.0	28 10 57.8	N245M	1221	16.83	F148W	1208	19.38	CTTS
			N263M	958	16.24	F154W	1207	19.19	
			N279N	1211	15.32	F169M	945	18.88	
FO Tau*	04 14 49.3	28 12 30.46	N245M	1221	19.77	F148W	1208		CTTS
			N263M	958	19.05	F154W	1207		
			N279N	1211	17.95	F169M	945		
FN Tau*	04 14 14.6	28 27 58.1	N245M	1221	18.64	F148W	1208	21.02	CTTS
			N263M	958		F154W	1207	20.85	
			N279N	1211	16.72	F169M	945	20.39	
CIDA 1*	04 14 17.520	28 06 9.0	N245M	1221	21.58	F148W	1188		CTTS
			N263M	958	20.61	F154W	1207		
			N279N	1211	20.08	F169M	945		
J041411.88 +281153.3*	04 14 11.88	28 11 53.31	N245M	1221	21.48	F148W	1188		CTTS
			N263M	958	20.60	F154W	1207		
			N279N	1211	19.63	F169M	945		
Anon 1*	04 13 27.216	28 16 22.8	N245M	1221	21.92	F148W	1188		WTTS
			N263M	958	20.82	F154W	1207		
			N279N	1211	19.63	F169M	945		
BS Tau	4 58 51.4	28 31 24.2	N242W	1214	17.92	F148W	1188	19.44	CTTS
			N245M	1228	18.11	F154W	1190	19.24	
			N263M	1225	17.83	F169M	1189	19.25	
V836 Tau	5 3 6.6	25 23 19.7	N242W	1228	19.54	F148W	1199	20.68	CTTS
			N245M	1227	19.68	F154W	1200	20.32	
			N263M	1205	19.05	F169M	1187	20.18	
HD283782	4 44 54.4	27 17 45.2	N242W	1209	16.20	F148W	1193	19.08	WTTS
			N245M	1228	15.98	F154W	1207	18.94	
			N263M	860	15.05	F169M	824	18.91	

NOTE—\*In the UVIT field of FM Tau, we found seven more TTS candidates having similar exposure times.

### 2.3. Spectral energy distribution

Out of 11 UVIT-detected TTS candidates, only seven are detected in both FUV and NUV bands, while the others are detected only in the NUV bands. Therefore, we performed two different approaches to fit the observed SEDs to estimate the stellar parameters. We made a two-component fit to the UV and optical part of the SEDs of the seven TTSs detected in both FUV and NUV bands; we used a stellar photospheric model and a blackbody (which represents the excess over the photosphere emission due to accretion shocks) to fit the observed SEDs to determine the excess UV luminosity, its equivalent temperature, and stellar parameters of the stars. We did not include IR regions for the SED fit as the excess emission in the IR region comes from the disk. For the remaining four TTSs, we only fit the photospheric models of dwarf stars to the optical part of the observed SEDs to estimate stellar parameters.

To construct observed SEDs, we cross-matched our sample with Gaia-DR3 (Gaia Collaboration et al. 2021; Babusiaux et al. 2022), APASS DR9 (Henden et al. 2015), and PanSTARRS (Magnier et al. 2020) for the optical; and 2MASS (Skrutskie et al. 2006), Spitzer and WISE (Wright et al. 2010) for IR region. We also included GALEX GR6/7 data for this analysis. We have used the virtual observatory (VO) tool, VOSA (VO SED Analyzer; Bayo et al. 2008) to generate SEDs by converting magnitudes into flux values for corresponding filters and then to fit the observed flux distribution with theoretical model spectra. We have obtained the distances from the Gaia-DR3 (Bailer-Jones et al. 2021). VOSA performs multiple iterations to get best-fitted spectra to observed flux distribution by varying  $T_{eff}$ ,  $\log(g)$ , metallicity, extinction, and scaling factor ( $M_d$ ) values and gives the best-fitted parameters after performing a  $\chi^2$  minimization. As these TTSs are in the solar neighbourhood, we con-



**Table 2.** Spectroscopic observations

Name	instruments	observation date (yyyy – mm – dd)	EW(H $\alpha$ )	mean EW(H $\alpha$ )	$L_{acc}$	$\dot{M}_{acc}$ ( $\times 10^{-9}$ )	Classification
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Anon 1	LAMOST	2014-11-05	-3.9	-3.9	—	—	WTTS
BS Tau	HCT	2021-01-17	-31.1	-33.1 $\pm$ 2.0	0.011 $\pm$ 0.001	2.17 $^{+0.16}_{-0.16}$	CTTS
		2021-09-06	-35.1				
CIDA 1	LAMOST	2012-01-04	-141.9	$-205.5^{+107.8}_{-67.7}$	$0.004^{+0.002}_{-0.001}$	$0.70^{+0.41}_{-0.28}$	CTTS
		2011-12-18	-224.8				
		2012-01-13	-133.3				
		2012-01-22	-97.7				
		2013-02-08	-271.7				
		2014-01-25	-242.1				
		2015-10-13	-231.5				
		2015-12-28	-273.2				
		2016-12-31	-232.9				
CW Tau	LAMOST	2014-01-25	-87.1	$-126.8^{+39.7}_{-105.4}$	$0.54^{+0.195}_{-0.57}$	$107.69^{+38.8}_{-113.65}$	CTTS
		2014-01-30	-232.2				
		2014-11-05	-60.4				
FM Tau	LAMOST	2014-01-30	-112.8	$-118.8^{+18.1}_{-24.1}$	$0.083^{+0.015}_{-0.021}$	$16.75^{+2.99}_{-4.12}$	
	HCT	2021-01-17	-100.7				
		2021-09-06	-142.9				
FN Tau	LAMOST	2014-01-25	-26.9	$-26.0^{+4.2}_{-3.4}$	$0.022^{+0.004}_{-0.003}$	$4.32^{+0.81}_{-0.68}$	CTTS
		2014-01-30	-21.8				
		2014-11-05	-29.4				
FO Tau	LAMOST	2011-12-18	-136.4	$-143.5^{+8.3}_{-29.2}$	$0.059^{+0.004}_{-0.014}$	$11.68^{+0.80}_{-2.88}$	CTTS
		2012-01-04	-172.7				
		2012-01-13	-135.9				
		2013-02-08	-135.2				
		2014-01-25	-137.4				
		2014-01-30	-158.2				
HD283782	HCT	2021-09-06	-1.9	-1.9	—	—	WTTS
V773 Tau	LAMOST	2014-11-05	-3.2	$-2.5^{+0.6}_{-0.7}$	—	—	WTTS
	HCT	2021-09-06	-1.9				
V836 Tau	HCT	2021-01-17	-8.9	$-13.3^{+4.4}_{-4.3}$	$0.013^{+0.005}_{-0.005}$	$2.60^{+1.0}_{-1.0}$	CTTS
		2021-09-06	-17.6				
J041411.88	LAMOST	2012-01-22	-319.4	$-357.4^{+38.0}_{-47.2}$	$0.002^{+0.001}_{-0.001}$	$0.49^{+0.01}_{-0.01}$	CTTS
		2012-01-23	-404.6				
		2015-12-28	-348.2				

NOTE—

sider that they all have similar metallicity as the Sun. We kept extinction as a free parameter to estimate its value from the best-fitted spectra. The scaling factor ( $M_d$ ) is used to scale the model flux to match the observed flux and is defined as  $(R_c/D)^2$  where  $R_c$  is the radius of the star and  $D$  is the distance to the star. For the stellar photosphere, we have used the BT-Settl-CIFIST model (Allard et al. 2011). We have used  $\log(g)$  values between 4 to 5 and the full range for  $T_{eff}$  from 1200 to 7000 K. In the case of the black body, we used a range of temperatures from 5000 to 20000 K.

In this study, we determined reduced  $\chi^2$  for the best fitted SEDs, which is defined as

$$\chi^2_{reduced} = \frac{1}{N-n} \sum_{k=1}^N \frac{(F_{o,k} - M_d \times F_{m,k})^2}{\sigma_{o,k}^2} \quad (1)$$

where  $N$  is the number of photometric data points,  $n$  is the number of input-free parameters,  $F_{o,k}$  is the observed flux, and  $F_{m,k}$  is the model flux.

In Figure 2, we have shown SEDs of the seven TTSs (detected in both FUV and NUV) fitted with model spectra. The observed fluxes are shown as cyan and blue points, where cyan points fall in the UV and optical regions of the energy distribution which is included in the dual component fitting

of model spectra. The blue points fall in the IR region and are not included in the fit. The black and grey lines represent the best-fitted black-body and BT-Settl-CIFIST spectra, respectively, to the cyan points. The combined flux of these two model spectra is shown as the red dashed line. The red points indicate the combined flux in different bands. The overlap between red and cyan points indicates the goodness of the two-component fitting. We notice that in the case of HD283782, combined flux matches very well in the IR region (not included in the fit) as well. Therefore, there is no IR excess present in HD283782, which indicates that the TTS does not have hot/warm dust around it. The values of reduced  $\chi^2$ , temperatures,  $\log g$ , and extinction ( $A_V$ ) corresponding to the best-fitted spectra are noted in the legends. The names of the sources are mentioned at the top of each plot. The figure suggests that FN Tau, V836 Tau, and HD283782 have high  $\chi^2$  values, which could be due to variability.

In Figure 3, we have shown SEDs of TTSs with no FUV detections. Due to the absence of FUV points, only the optical region of the observed SED is fitted with synthetic dwarf spectra (BT-Settl-CIFIST) to get the stellar parameters of these TTSs. We have used  $T_{eff}$ ,  $\log(g)$ , and  $A_V$  as free parameters, and metallicity to be fixed at Solar value. Blue and cyan points in Figure 3 are observed SEDs, where only cyan points are included in the fitting process. The gray spectrum indicates the best-fitted model spectrum to the optical region of the observed SED. The red point indicated the expected flux due to the best-fitted model spectrum. The best-fitted parameters are mentioned in the legend. Anon 1 shows almost no excess in the IR regions, indicating a lack of hot/warm dust around it.

### 3. RESULTS AND DISCUSSION

The SED analysis provides us with fundamental parameters of the TTSs, i.e.,  $T_{eff}$ ,  $\log g$ , radius, mass, and bolometric luminosity ( $L_{bol}$ ) of the central stars. As mentioned on the VOSA website, the fitting process and the predicted flux are relatively less sensitive to  $\log g$ . This poses a challenge to put direct constraints on the masses of the components since a slight change in  $\log g$  can create a large difference in the estimated mass. Therefore, we do not include the estimations of mass and  $\log g$  in our analysis. The values of other parameters are listed in Table 3. The luminosity of the black-body provides a direct measure of the accretion luminosity/chromospheric luminosity. In Table 3, we listed the value of bolometric luminosity enclosed within the black-body spectrum ( $L_{acc}$ ) and black-body temperature ( $T_{BB}$ ). We have also estimated the spectral type of each TTS using  $T_{eff}$ -spectral type relation (Pecaut & Mamajek 2013) and listed in column 7 of Table 3. We find that TTS have a  $T_{eff}$  range from 3000 K to 4600 K and spectral types of K and M. The  $T_{BB}$  ranges from 6800 K to 10300 K.

#### 3.1. UV excess as a indicator of accretion

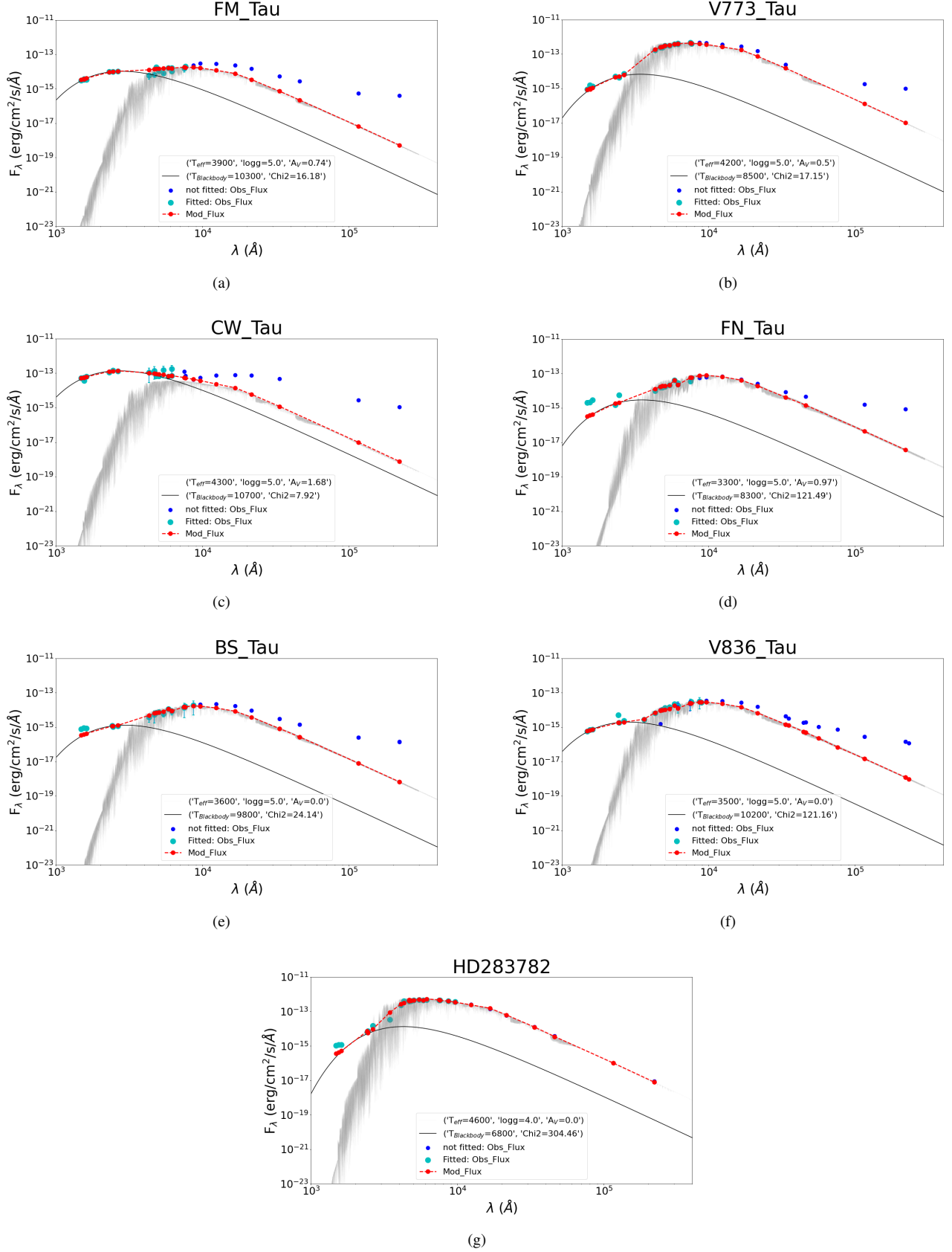
We notice in Figure 2 that V773 Tau and HD283782 emit negligible amounts of excess emission in NUV bands above the photospheric emission compared to that found in the FUV

bands. Whereas, in the other five sources we observe a large excess emission in both NUV and FUV bands. In Figure 3, we further notice that Anon1 has less excess NUV bands compared to other sources. The presence/absence of NUV excess appear to divide sources into two different categories.

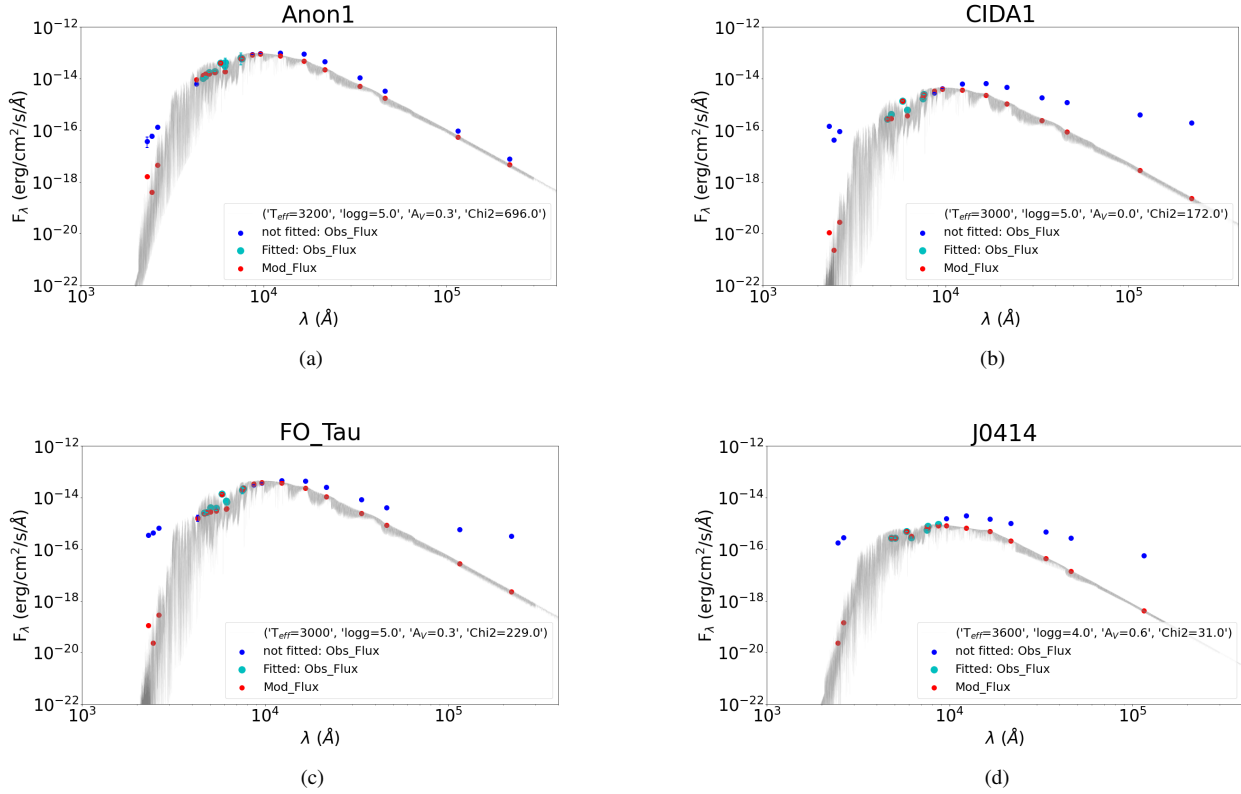
However, we need to quantitatively estimate the amount of excess emission in all the sources and compare them before giving any conclusion. To quantify the excess flux observed in the FUV and NUV regions, we define excess emission in a particular band as  $(\frac{(\text{dereddened observed flux})}{(\text{model flux})_{BT-Settl-CIFIST}} - 1)$ . To demonstrate UV excess, we used the N245M filter in the NUV and the F148W band in the FUV regions, as these are common bands for all the sources. The difference in photospheric temperature or spectral types of the stars could also lead to variation in the excess emission. For a hotter star, the excess emission may appear low, which can also affect the blackbody temperature. Therefore, we have plotted NUV and FUV excess as a function of effective temperature ( $T_{eff}$ ) in the upper panel of Figure 4 and as a function of blackbody temperature ( $T_{BB}$ ) in the lower panel.  $T_{eff}$  and  $T_{BB}$  are estimated from SED fitting. The sources detected in both FUV and NUV are marked as blue points, while the sources with only NUV detection are marked in orange. We can see that there are two groups of population, independent of their spectral types and blackbody temperature, separated by a black dashed line. The presence of high UV excess ( $>10^3$  in NUV and  $>10^7$  in FUV) suggests that these eight sources (FM Tau, CW Tau, FN Tau, BS Tau, V836 Tau, CIDA1, FO Tau and J0414) could possibly be CTTS, while V773 Tau, HD283782 and Anon1 are probable WTTS candidates with comparatively little excess in UV. Comparatively low UV excess with almost no IR excess in HD283782 indicates that it is an example of disk-less WTTS. A more careful inspection suggests that stars with higher UV excess (or the probable CTTS) also tend to have hotter  $T_{BB}$  compared to the stars with lesser UV excess, with FN tau as an exception. However, we need more sources with simultaneous UV observations to confirm this aspect. We classify the stars emitting  $>10^3$  ( $>10^7$ ) excess emission in NUV (FUV) as CTTS, while the other group of stars are classified as WTTS. Our classification based on the UV excess is listed in the Table 1. We, however, require further evidence from spectroscopic observations before confirming their classification as CTTS or WTTS, as CTTSs are expected to show strong  $H\alpha$  emission compared to WTTS.

#### 3.2. $H\alpha$ line emission as an accretion indicator

We analyzed spectra obtained from both the HFOSC/HCT and LAMOST for our sources. We estimated the equivalent width of  $H\alpha$  line emission ( $EW(H\alpha)$ ) after subtracting continuum flux from the spectra. In Table 2, we have listed the  $EW(H\alpha)$  for each source obtained from the multi-epoch observations with different telescopes (column 3). Names of the telescopes and the dates of observations are also mentioned in columns 2 and 3, respectively. We notice that  $EW(H\alpha)$  of FM Tau and V773 Tau from HCT observations matches well with that obtained from the LAMOST spectra. We are un-



**Figure 2.** SEDs of TTSs are shown here. The names of the TTSs are mentioned on top of each sub-figure. The grey and black lines represent the best-fitted synthetic black body and dwarf spectra, respectively, on observed fluxes (cyan and blue points). Cyan points are included in the fitting algorithm, avoiding the IR region marked as blue. The red dashed- line indicates the expected combined model flux from the fitted synthetic spectra.

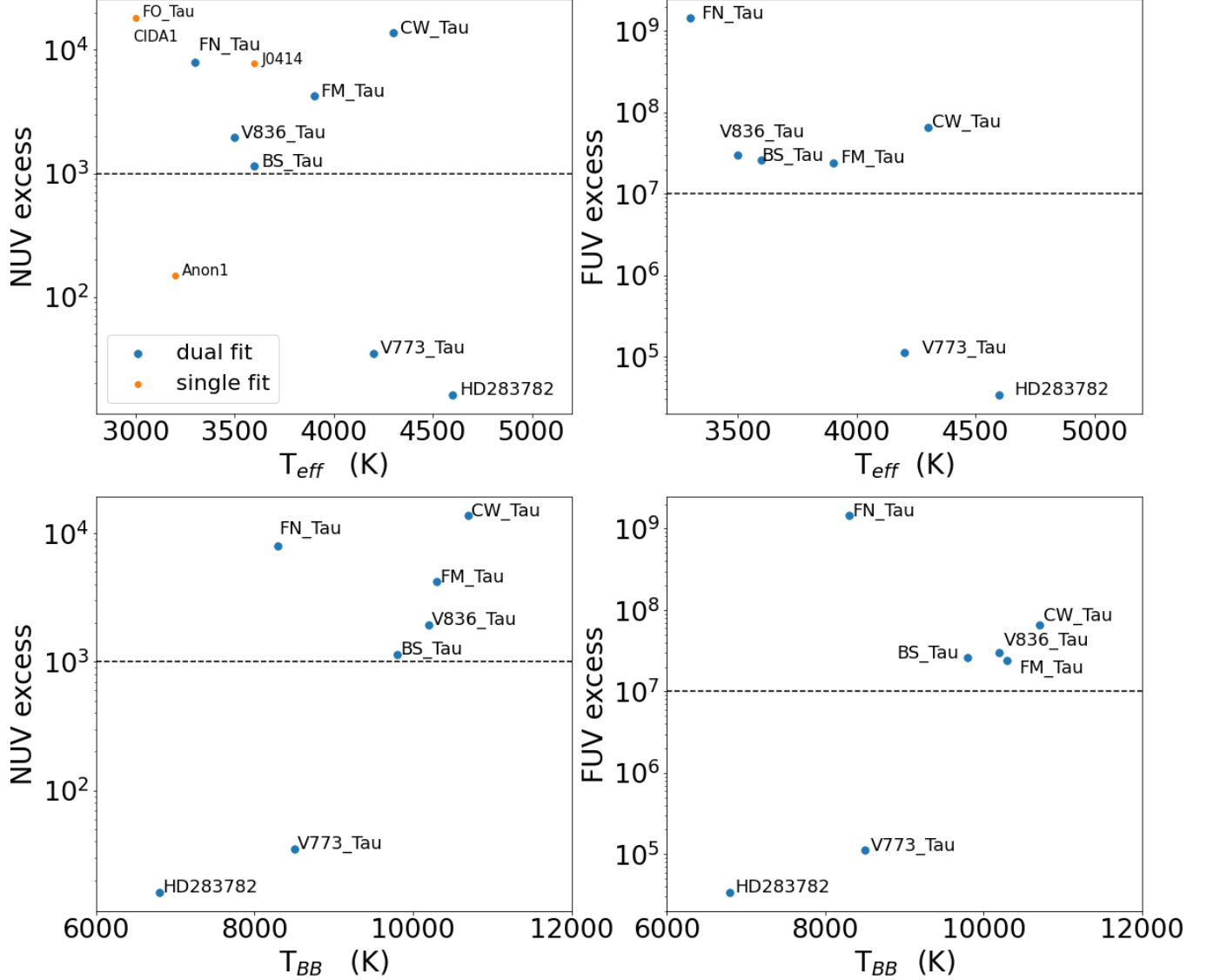


**Figure 3.** The figure represents the same as Figure 2 but only the optical region of the SEDs are fitted with theoretical dwarf spectra (BT-Settl-CIFIST).

**Table 3.** stellar properties estimated from SED analysis

TTS	$T_{BB}$	$T_{eff}$	Radius	$L_{bol}$	Spectral Type	$L_{acc}$	$\dot{M}_{acc}$
Name	(K)	(K)	( $R_{\odot}$ )	( $L_{\odot}$ )		( $L_{\odot}$ )	( $10^{-9} \times M_{\odot} \text{yr}^{-1}$ )
(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
FM Tau	10300	3900	$0.73 \pm 0.03$	$0.11 \pm 0.001$	K7	$0.022 \pm 0.0002$	$4.44 \pm 0.03$
V773 Tau	8800	4200	$3.02 \pm 0.03$	$2.54 \pm 0.02$	K6	$0.018 \pm 0.0002$	—
BS Tau	9800	3600	$0.96 \pm 0.03$	$0.14 \pm 0.003$	M2	$0.004 \pm 0.0001$	$0.78 \pm 0.03$
V836 Tau	10200	3500	$1.54 \pm 0.04$	$0.33 \pm 0.003$	M3	$0.01 \pm 0.0001$	$1.93 \pm 0.03$
HD283782	6800	4600	$3.34 \pm 0.05$	$4.45 \pm 0.028$	K4	$0.073 \pm 0.0006$	—
CW Tau	10700	4300	$0.81 \pm 0.03$	$0.21 \pm 0.002$	K5.25	$0.325 \pm 0.004$	$64.9 \pm 0.09$
FN Tau	8300	3200	$2.17 \pm 0.04$	$0.50 \pm 0.001$	M5	$0.009 \pm 0.00002$	$1.76 \pm 0.004$
FO Tau		3000	$2.24 \pm 0.07$	$0.37 \pm 0.001$	M6.5		
Anon 1		3200	$2.59 \pm 0.04$	$0.64 \pm 0.001$	M5		
J041411.88		3600	$0.20 \pm 0.04$	$0.006 \pm 0.001$	M2		
CIDA 1		3000	$0.61 \pm 0.04$	$0.027 \pm 0.001$	M6.5		





**Figure 4.** The figure shows the relation between temperature and UV excess.

able to obtain a multi-epoch of observation for Anon 1 and HD 283782. In column 5, we have listed average values of  $\text{EW}(\text{H}\alpha)$  corresponding to each TTS, and errors associated with it indicate the range in  $\text{EW}(\text{H}\alpha)$ . As the strength of  $\text{H}\alpha$  provides an indirect indication of accretion rate, a large range in  $\text{EW}(\text{H}\alpha)$  in CIDA 1, CW Tau, and J041411 suggests a large variation in accretion rate in these TTS.

The  $\text{H}\alpha$  line strength has often been used to distinguish between CTTS and WTTS in the literature (White & Basri 2003). WTTS show weak emission due to chromospheric activity, while comparatively strong emission from CTTS is produced due to accretion. However, there is no unique value of  $\text{EW}(\text{H}\alpha)$  that act as a dividing line for this classification (Barrado y Navascués & Martín 2003; White & Basri 2003). Barrado y Navascués & Martín (2003) provided  $\text{EW}(\text{H}\alpha)$

values as a function of spectral types, derived from the observed saturation limit for the chromospheric activity (blue line in Figure 5). Whereas, (White & Basri 2003) provided maximum  $\text{EW}(\text{H}\alpha)$  values for WTTS for different ranges in spectral types (black dashed line in Figure 5). We have over-plotted average  $\text{EW}(\text{H}\alpha)$  values of our sample TTSs in Figure 5. The spectral types are estimated from photospheric temperature based on the correlation given in Pecaut & Mamajek (2013), listed in Table 3. Figure 5 shows that FM Tau, BS Tau, CW Tau, CIDA 1, FN Tau, and FO Tau have high values of  $\text{EW}(\text{H}\alpha)$  with respect to the expected values from WTTS with similar spectral types. These stars also show high UV excess, as discussed in the previous section, indicating that their classification as CTTS is robust. Except for BS Tau and FN Tau, all other sources discussed above show

significant variation in the  $EW(H\alpha)$ , suggesting a large variation in the accretion rate. In the next section, we estimate and discuss the accretion luminosity and mass accretion rate of these sources. We, however, need more followup observations for a detailed study of their variability.

Anon 1, V773 Tau, and HD 283782 have equivalent widths less than that expected for their spectral types, which indicates that these TTS can be classified as WTTS. From the SEDs, we have also seen relatively low UV excess over photospheric emission. Both these scenario suggests that these are WTTSs. Figure 5 also shows that V836 Tau falls on the line separating CTTS from WTTS and the range in the  $EW(H\alpha)$  extends on both sides, making it difficult to classify. However, we notice a large amount of UV excess emission as shown in Figure 4, which is comparable to that found in other CTTS, suggesting that V836 Tau is a CTTS. We also notice that V836 Tau changes its  $EW$  from 8.88 to 17.6 in the two epochs of observation, which corresponds to  $\sim 100\%$  increase in the  $EW$ . These observations suggests that the star is going through a variable accretion rate. Therefore, based on both UV excess and  $EW(H\alpha)$ , we suggest that V836 Tau is a slowly accreting CTTS with a variable accretion rate. Further monitoring observations of V836 Tau is required to understand its accretion properties. Our classification based on the spectroscopic observations is listed in the Table 2.

Our classification of these sources matches well with the previous literature. From the literature, we find that FM Tau, CW Tau, FN Tau and FO Tau are classified as CTTS, while V773 Tau and HD283782 are classified as WTTS (Herbig & Bell 1988; Kenyon et al. 1998; Valenti et al. 2003; Ingleby et al. 2013; McClure et al. 2013; Gómez de Castro et al. 2015), which agrees with our classification. BS Tau and V836 Tau are classified as WTTS based on the UV-NIR colour-colour relation (Gómez de Castro et al. 2015), contrary to our classification of CTTS for both sources. Based on HST FUV spectroscopic observations, V836 Tau is classified as slowly accreting CTTS (Ingleby et al. 2013). However, both UV excess and  $EW(H\alpha)$  values from our analysis indicate that BS Tau and V836 Tau are CTTS. We did not find any classification for CIDA 1, J0414, and Anon 1 in the literature. Thus from our analysis, we reconfirm that V836 Tau is CTTS and for the first time we report BS Tau, CIDA 1, and J0414 are CTTS and Anon 1 is WTTS. This study demonstrates the importance of multi-wavelength SED analysis and in particular, the simultaneous FUV and NUV observations to classify the TTS as classical or weak-line.

### 3.3. Relation between $H\alpha$ luminosity and accretion luminosity

In this study, we have determined excess UV flux by fitting the excess emission with the black-body spectrum. The flux enclosed within the fitted black-body spectrum is nothing but the excess UV emission due to accretion in CTTS and chromospheric activity in the WTTS. Hence, the bolometric luminosity of the black-body spectrum provides the direct measure of accretion luminosity in CTTS. We used this luminosity value to calculate mass accretion rate in CTTS. Mass

accretion rate ( $\dot{M}$ ) and accretion luminosity are related by

$$L_{acc}/L_{\odot} = (GM_*\dot{M}/R_*) \times (1 - R_*/R_{in}) \quad (2)$$

where  $M_*$  and  $R_*$  are stellar mass and radius and  $R_{in}$  is the disk truncation radius from which the gas falls onto the star.  $R_{in}$  is typically assumed to be  $\sim 5 R_*$  (Gullbring et al. 1998). The error introduced by this assumption on the measured mass accretion rates, considering that  $R_{in}$  for a pre-main sequence star can span from 3 to  $8 R_*$ , is less than 20%. Therefore, the above equation can be written as

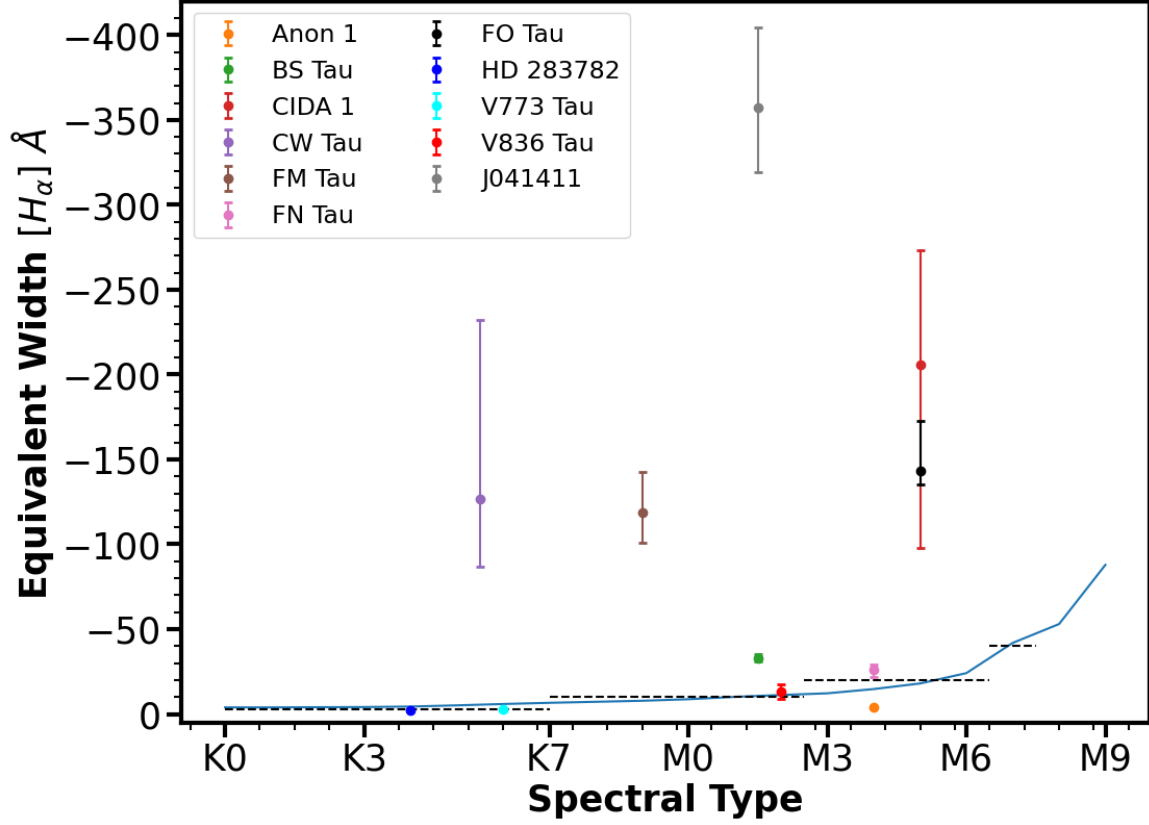
$$\dot{M}_{acc} = (1 - R_*/R_{in}) \times (L_{acc}R_*/GM_*) \sim 1.25(L_{acc}R_*/GM_*) \quad (3)$$

We have considered  $R_*/M_* \sim 5 R_{\odot}/M_{\odot}$  and used above equation 3 to estimate  $\dot{M}_{acc}$ . The values are listed in the last column of Table 3. We have only calculated the mass accretion rate for the stars classified as CTTS.  $L_{acc}$  and  $\dot{M}_{acc}$  estimated from excess UV flux provides a direct measure of these parameters.

$EW(H\alpha)$  is often used as a proxy for accretion (White & Basri 2003). However,  $EW(H\alpha)$  is secondary indicator for accretion. Therefore, we tried to find the correlation between  $L_{acc}$  from UV excess and  $L_{H\alpha}$ . We used extinction corrected Pan-STARRS r band flux density as a proxy for the continuum flux density underlying  $H\alpha$  line and the distance obtained from Gaia-DR3 to calculate  $L_{H\alpha}$  from average  $EW(H\alpha)$  values listed in Table 2. The continuum flux density at  $H\alpha$  is given as (Mathew et al. 2018),

$$F_{\nu,cont}(H\alpha) = F_{\nu,0} \times 10^{(-\frac{r_0}{2.5})}$$

where  $F_{\nu,0} = 3.08 \times 10^{-23} \text{ W m}^{-2} \text{ Hz}^{-1}$  and  $r_0$  is the extinction corrected Pan-STARRS magnitude. The extinction is obtained from the SED fitting as listed in Table 3. In Figure 6, we plotted  $L_{acc}$  estimated from UV excess vs that estimated from  $(L_{H\alpha})$ , which shows a linear correlation (red line) between them with a slope of  $1.21 \pm 0.17$  and intercept of  $2.18 \pm 0.56$ . There are also previously reported correlations between luminosity of  $H\alpha$  ( $L_{H\alpha}$ ) and accretion luminosity ( $L_{acc}$ ) (Vogt et al. 1994; Herczeg & Hillenbrand 2008; Dahm 2008; Fang et al. 2009; Ingleby et al. 2013). We compare our relation with that estimated by previous studies in Table 4 and noticed that our relation matches quite well with the slope and intercept values with the previous estimation from the literature. However, we get a relatively large error in its intercept value, which could be due to the small sample size. A large sample with simultaneous observations in UV and optical spectroscopy is required for a better correlation. We have also used this relation to estimate  $L_{acc}$  from  $L_{H\alpha}$  for all the CTTS listed in Table 2. This help us to calculate  $L_{acc}$  for the TTS with no FUV observations for which we could not estimate UV luminosity. We then also calculated  $\dot{M}_{acc}$  using Equation 3. The values of  $L_{acc}$  and  $\dot{M}_{acc}$  are listed in Table 2. We notice that J0414, CIDA 1, V836 Tau, FN Tau, and BS Tau are the slowly accreting CTTSs with a mass accretion rate a few times  $10^{-9} M_{\odot} \text{ yr}^{-1}$ , while FM Tau, CW Tau, and FO Tau are found to have comparatively higher accretion rate (a few times  $10^{-8} M_{\odot} \text{ yr}^{-1}$ ).



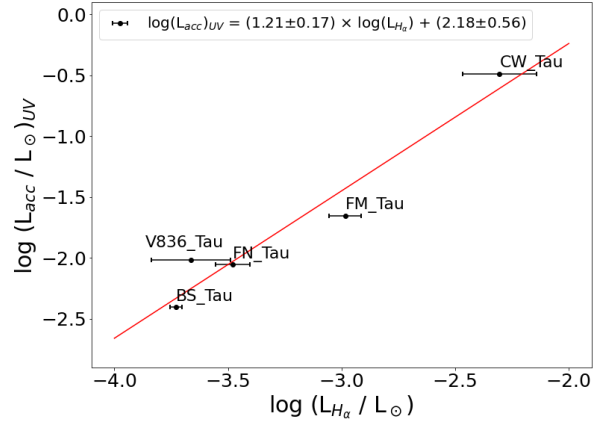
**Figure 5.** The solid line (Barrado y Navascués & Martín 2003) and dashed line (White & Basri 2003) indicate relations between spectral types and  $H\alpha$  equivalent width, which separates CTTS from WTTS. The TTS studied in this paper are also over-plotted.

slope (m)	intercept (c)	reference
$1.20 \pm 0.11$	$2.0 \pm 0.4$	Herczeg & Hillenbrand (2008)
$1.18 \pm 0.26$	$2.19 \pm 0.64$	Dahm (2008)
$1.25 \pm 0.07$	$2.27 \pm 0.23$	Fang et al. (2009)
$1.31 \pm 0.03$	$2.63 \pm 0.13$	Manara et al. (2012)
$1.0 \pm 0.2$	$1.3 \pm 0.7$	Ingleby et al. (2013)
<b><math>1.21 \pm 0.17</math></b>	<b><math>2.18 \pm 0.56</math></b>	<b>this work</b>

**Table 4.** Compare the empirical relations between  $L_{acc}$  and  $L_{H\alpha}$  with literature.  $\log(L_{acc}/L_{\odot}) = m \times \log(L_{H\alpha}/L_{\odot}) + c$

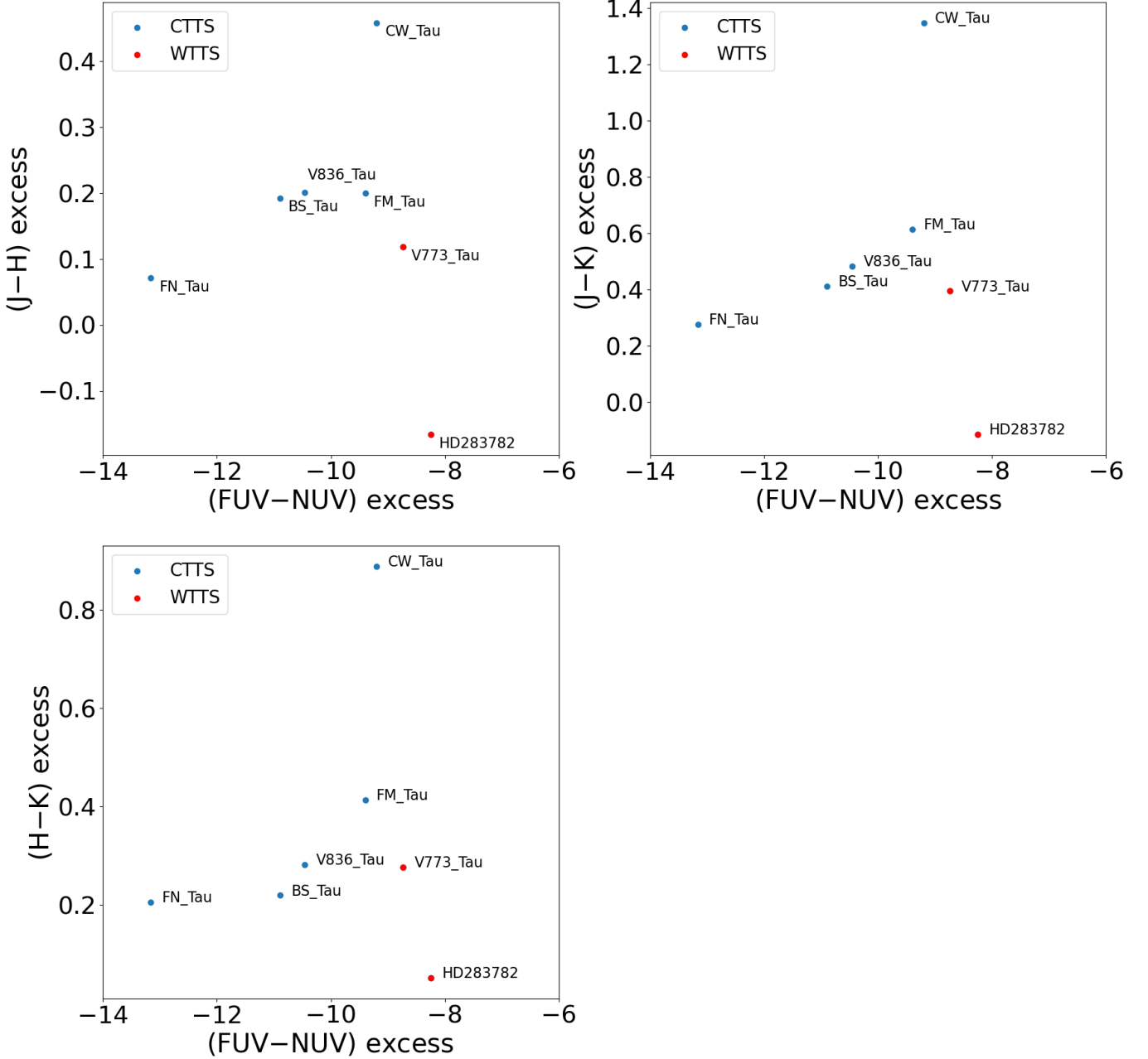
### 3.4. Relation between UV excess and IR excess

The NIR color excess if taken as evidence for the presence of circumstellar disks around TTS. The strength of the infrared colour excess indicates the amount of dust and gas in these disks. A strong excess suggests a substantial amount of material in the disk, while a weaker excess may indicate a less massive or more evolved disk. The strong excess in FUV and NUV suggests the presence of significant accretion onto the stars, while the high FUV and relatively low or no NUV excess suggest that the UV emission originates from chromospheric activity. FUV emission from the star plays a significant role in heating gas disks and driv-



**Figure 6.** The figure shows the relation between accretion luminosity estimated using UV luminosity and  $(L_{H\alpha})$ .

ing massive thermal winds which deplete the disk material. Hence, excess in  $(FUV - NUV)$  color in WTTS stars will tell us if the stars are dominant in chromospheric activity, while for CTTS, it tells us whether the stars are dominant



**Figure 7.** The figure shows the relation between IR excess and UV excess.

in FUV emission. Also, the comparison between UV color and IR color helps us to identify the changes in disk morphology (primordial gas-rich disks or evolved or transitioning to a debris disk) from FUV bright stars to FUV faint stars. The UV colour index is plotted against J-K, J-H and H-K infrared color excess from 2MASS observations in Figure 7. H-K excess is considered to be a good estimator of the accretion rate (Meyer et al. 1997). The colour excess is defined as:  $-2.5 \times [\log(\frac{(\text{observed flux})_{\text{Band1}}}{(\text{observed flux})_{\text{Band2}}}) - \log(\frac{(\text{expected flux})_{\text{Band1}}}{(\text{expected flux})_{\text{Band2}}})]$ , in magnitude unit. For CTTS,

we notice that stars with lower IR colour excess, i.e., with weaker inner disks, appear bluer in the (FUV - NUV) color, which means they have stronger FUV emission. This suggests that strong FUV emission might have caused the depletion of the gas and dust in the circumstellar disk in CTTS. The WTTS seem to be following a different slope relation compared to CTTS but with two WTTS data points, it is not so conclusive. A larger sample of CTTS and WTTS is required for better understanding of this relation.

## 4. SUMMARY

In this study, we present the accretion properties of eleven TTSs in the TMC, namely FM Tau, BS Tau, V836 Tau, HD283782, V773 Tau, CW Tau, FN Tau, FO Tau, Anon 1, CIDA 1, and 2MASS J04141188+2811535. This is the first UVIT study of T Tauri stars and highlights the significance of simultaneous multi-band UV observations of TTSs to study their accretion properties. Out of 11, seven are detected in both FUV and NUV bands, while the remaining four are detected only in NUV. We report, for the first time, the UV photometry of 2MASS J04141188+2811535 (not detected in GALEX, which could be due to small exposure time), and the FUV photometry of FN Tau.

For the sources detected in both FUV and NUV, we modelled excess UV flux emitted by TTS as black-body emission and measured the excess UV emission by two-component SED fitting to the UV and optical regions of the observed SED. From the SED fit, we obtained fundamental stellar parameters (temperature, extinction, radius, and bolometric luminosity) of these TTSs. We also estimated black-body temperature and luminosity corresponding to the excess UV emission. For the sources with only NUV detection, we only fit the optical region of the SEDs to obtain the stellar parameters and excess emission in NUV bands.

We noticed there are two categories of TTSs based on the excess UV emission: one shows strong excess emission ( $>10^3$  in NUV and  $>10^7$  FUV) over the photosphere; the other with excess emission mostly in FUV ( $\lesssim 10^5$ ) and a little excess in NUV ( $\lesssim 10^2$ ). We classify the TTSs with strong excess emission in both FUV and NUV as CTTS, and the other group as WTTS. This study shows that UV excess can be used as a tool to distinguish CTTS and WTTS.

We found that classification of TTS as classical or weak-line based on the spectral type vs EW( $H\alpha$ ) relation (Barrado y Navascués & Martín 2003; White & Basri 2003) matches

well with that made based on UV excess. Our classification also matches well with the literature. From our analysis, we reconfirm that V836 Tau as CTTS and for the first time we report BS Tau and J0414 as CTTS, and Anon 1 as WTTS.

We found that  $H\alpha$  luminosity and accretion luminosity (from UV luminosity) are linearly correlated with a slope of  $1.21 \pm 0.17$  and an intercept of  $2.18 \pm 0.56$ . The correlation also matches well with previous estimates by (Herczeg & Hillenbrand 2008; Dahm 2008; Fang et al. 2009; Manara et al. 2012). From the mass accretion rate calculation based on UV luminosity and  $H\alpha$  luminosity, we found that CW Tau, FM Tau and FO Tau are going through a strong accretion phase with an accretion rate  $> 10^{-8} M_{\odot} \text{yr}^{-1}$ , while other CTTS are accreting at a slower rate ( $\sim$  a few times  $10^{-9} M_{\odot} \text{yr}^{-1}$ ). The study brings out the importance of multi-wavelength SED analysis and simultaneous FUV and NUV observation to get a better estimation of the accretion luminosity and accretion rate of TTS.

Comparing the UV colour with the IR colour, we notice that stars with higher IR colour excess, i.e., the presence of a substantial amount of material in the disk, appear redder in the (FUV – NUV) colour, and vice versa. This suggests that stronger FUV emission might have caused the depletion of the gas in the disk. However, a study with a large number sample is required for a better understanding of this relation.

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