Constraints to the magnetospheric properties of T Tauri stars – I. The C ii], Fe ii] and Si ii] ultraviolet features

Fatima López-Martínez* and Ana Inés Gómez de Castro
AEGORA Research Group, Universidad Complutense de Madrid, Plaza de Ciencias 3, E-28040 Madrid, Spain

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ABSTRACT

The C ii] feature at ~2325 Å is very prominent in the spectra of T Tauri stars (TTSs). This feature is a quintuplet of semiforbidden transitions excited at electron temperatures around 10 000 K that, together with the nearby Si ii] and Fe ii] features, provides a reliable optically thin tracer for accurate measurement of the plasma properties in the magnetospheres of TTSs. The spectra of 20 (out of 27) TTSs observed with the Space Telescope Imaging Spectrograph on board the Hubble Space Telescope have good enough signal-to-noise ratio at the C ii] wavelength. For these stars, we have determined electron densities (n_e) and temperatures (T_e) in the line emission region as well as the profile broadening (σ). For most of the stars in the sample (17), we obtain 10^{4.1} ≤ T_e ≤ 10^{4.3} K and 10^8 ≤ n_e ≤ 10^{12} cm^{-3}. These stars have suprathermal line broadening (35 ≤ σ ≤ 165 km s^{-1}), except TW Hya and CY Tau with thermal line broadening. Both C ii] line luminosity and broadening are found to correlate with the accretion rate. Line emission seems to be produced in the magnetospheric accretion flow, close to the disc. There are three exceptions: DG Tau, RY Tau and FU Ori. The line centroids are blueshifted indicating that the line emission in these three stars is dominated by the outflow.

Key words: stars: magnetic field – stars: pre-main sequence – stars: winds, outflows – ultraviolet: stars.

1 INTRODUCTION

T Tauri stars (TTSs) are young and low-mass (<3 M⊙) pre-main-sequence stars with strong and complex magnetic fields and a surrounding disc that is truncated near the corotation radius by interaction with the magnetic field. From the observational point of view, TTSs are split into two main groups: Classical TTSs (CTTSs) and Weak lined TTSs (WTTSs). CTTSs are accreting mass from the disc whereas WTTSs have no or very little spectral signatures of accretion. The material in the inner part of the disc is ionized by the stellar radiation and channelled through the magnetic field lines (Uchida & Shibata 1984; Koenigl 1991). The gas from the disc is accelerated to almost free-fall velocity before it reaches the stellar surface forming an accretion shock (see e.g. the reviews by Bouvier et al. 2007; Gómez de Castro 2013a). Detailed simulations of the interaction between the stellar field and the inner disc show a complex dynamics of the magnetospheric flow that depends on the field properties and its stability (Romanova et al. 2012; Kurosawa & Romanova 2013). Some analytical expressions for the hotspot shapes and the magnetospheric radius have been provided by Kulkarni & Romanova (2013).

The interaction between the star, disc and magnetic field produces an excess emission at different wavelengths that affects the evolution of the disc itself and the circumstellar environment. The atmospheric and magnetospheric energy output is released mainly in the ultraviolet (UV) spectral range. Thus, there is a relatively large number of spectral features in the UV that can be used as potential tracers of the physical conditions in TTS. Different emission lines in the UV wavelength range provide different information about the regions in which they are formed, the involved physical processes and the system geometry. For example, the Mg ii resonance doublet at 2795.5 and 2802.7 Å is produced in the chromosphere of TTS and it is one of the strongest features in UV spectra of TTS. Mg ii is sensitive to, and can be used as a good tracer of, atmosphere and outflow/wind in TTS (Ardila et al. 2002b; Calvet et al. 2004; Ingleby et al. 2013, Lopez-Martinez & Gómez de Castro, submitted). N v, C iv, He ii and Si iv are good tracers of hot gas and accretion processes in TTSs. The relationship between these lines and mass accretion in TTSs has been already studied by different authors (Johns-Krull, Valenti & Linsky 2000; Ardila et al. 2002a, 2013; Ingleby et al. 2011; Yang et al. 2012; Gómez de Castro & Marcos-Arenal 2012; Gómez de Castro 2013b).

The semiforbidden lines of the C ii] quintuplet (wavelengths: 2324.21, 2325.4, 2326.11, 2327.64, 2328.83 Å) are not observed in WTTSs; however, they are readily detected in CTTSs, even in low-mass accretors (Lamzin 2000). This multiplet seems to be a

*E-mail: fatimalopezmar@gmail.com

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very sensitive tracer of accretion or outflows (Calvet et al. 2004; Gómez de Castro & Ferro-Fontán 2005; Ingleby et al. 2013). Calvet et al. (2004) and Ingleby et al. (2013) analysed these lines in low resolution spectra and found a relationship between the C II luminescence and the accretion luminosity. The study of the C II flux ratios within a small range of wavelengths provides a good opportunity to investigate TTS properties because they are optically thin and their ratios do not depend on the geometry of the accretion system and are only slightly affected by the large uncertainties associated with extinction determination. It is known that the relative intensities of the emission lines of the C II multiplet are sensitive to the electron density in the range \( n_e \approx 10^{10} \text{cm}^{-3} \) (Stencel et al. 1981; Hayes & Nussbaumer 1984a, b; Keenan et al. 1986). Plasma in the magnetospheres and atmospheres of CTTSs is within this density range. However, line blending makes it difficult to identify the individual features and to measure the lines ratios (see e.g. Lamzin 2000; Kravtsova & Lamzin 2002 observations of RU Lup and DR Tau, respectively).

In this work, we present for the first time a study of C II line ratios in a sample of 20 CTTSs using 30 medium-resolution spectra. We found the best-fitting spectrum to the data using a grid of simulated profiles computed for a broad range of electron densities and temperatures. The log of observations, the characteristics of the CTTSs sample and the profiles are described in Section 2. The numerical method used to derive the individual lines fluxes and the properties of the radiating plasma is presented in Section 3, that also includes the limitations of the method and the final results. In Section 4, we present the plasma properties obtained with our procedure and they are compared with the accretion rates derived from Ingleby et al. (2013). To conclude, in Section 5, we provide a brief summary of the main results.

2 THE C II PROFILE OF CTTS

Our sample consists of 27 CTTSs observed with the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST); no C II emission is detected in WTTSs. Most of the sources (17 of 27) are located in Taurus-Auriga Molecular Cloud. The rest of the sources are in \( \eta \) Chamaeleon (2), \( \epsilon \) Chamaeleon (1), Chamaeleon I (2), TW Hydra Association (2), Orion (1) and Upper Scorpius (1). DK Tau, HN Tau (Correia et al. 2006), CV Cha (Bary et al. 2008) and UX Tau (Nguyen et al. 2012) are binaries with companions at distances of 2.304, 3.109, 11.4 and 5.9\,arcsec, respectively, that are resolved by STIS. T Tau (Furlan et al. 2006), FU Ori (Wang et al. 2004) and DF tau (Unruh, Collier Cameron & Guenther 1999) are close binaries at distances 0.7, 0.5 and 0.09\,arcsec, respectively. CS Cha is a spectroscopic binary (Guenther et al. 2007). Several stars show evidence of transitional discs, but they are still accreting: CS Cha, DM Tau, GM Aur, TW Hya and UX Tau (Espaillat et al. 2010). In some sources of our sample jets/outflows have been detected: RT Tau (St-Onge & Bastien 2008), DG Tau (Coffey, Bacciotti & Podio 2008), T Tau (Furlan et al. 2006), SZ 102 (Comerón & Fernández 2011), AA Tau, DF Tau, HN Tau and SU Aur (Howard et al. 2013).

The sample is formed of 42 medium-resolution (\( R \approx 30000 \)) spectra obtained with grating E230M; the log of data is provided in Table 1. We have selected spectra with S/N > 2; the signal-to-noise ratio (S/N) has been calculated over the whole feature as described in Section 3.3. The spectra are shown in Fig. 1. No significant variations are detected in the spectrum of sources with multiple observations, except for DS Tau (see Appendix A); note that though the C II flux of DS Tau drops by a factor of 2 between two observations, no significant profile shape variations are noticeable.

| Star   | Obs date (yy-mm-dd) | Data set | Exp time (s) | S/N |
|--------|---------------------|----------|--------------|-----|
| AA Tau | 11-01-07            | ob6ba7030| 1462.2       | 3.21|
| CS Cha | 11-06-01            | ob6b6b030| 1785.2       | 1.65|
| CV Cha | 11-04-13            | ob6b18020| 2598.2       | 3.30|
| CY Tau | 00-12-06            | o5cf03020| 738          | 2.54|
| DE Tau | 10-08-20            | ob6b1a803| 1388.1       | 3.58|
| DF Tau | 99-09-18            | o5kc01020| 1670.2       | 14.72|
| DG Tau | 01-02-20            | o6303010 | 2345         | 1.87|
|        | 01-02-20            | o6303020 | 2923         | 2.66|
|        | 01-02-20            | o6303030 | 2923         | 2.56|
|        | 01-02-20            | o6303040 | 2923         | 1.91|
| DK Tau | 10-02-04            | ob6bb2030| 854.4        | 0.81|
| DM Tau | 10-08-22            | ob6ba2030| 1330.1       | 1.37|
| DN Tau | 11-09-10            | ob6ba4030| 1441.2       | 1.72|
| DR Tau | 00-08-29            | o5cf02020| 916          | 1.12|
|        | 01-02-09            | o6304010 | 2327         | 2.04|
|        | 01-02-09            | o6304020 | 2880         | 2.26|
|        | 10-02-15            | ob6bb4030| 881.3        | 0.44|
| DS Tau | 00-08-24            | o5cf01020| 878          | 2.06|
|        | 01-02-23            | o6308010 | 2345         | 2.27|
|        | 01-02-23            | o6308020 | 2923         | 2.12|
| FM Tau | 11-09-21            | ob6ba0030| 1401.2       | 0.64|
| FU Ori | 01-02-22            | o6307020 | 2880         | 2.54|
| GM Aur | 10-08-19            | ob6ba1030| 1300.5       | 3.61|
| HN Tau | 10-02-10            | ob6ba9030| 807.5        | 1.24|
| PDS 66 | 11-05-23            | ob6b23030| 1725.2       | 11.68|
| RECX15 | 10-02-05            | ob6bb7030| 916.4        | 2.45|
| RECX11 | 09-12-12            | ob6bb4030| 697.8        | 2.32|
| RT Tau | 01-02-19            | o6301010 | 2353         | 7.47|
|        | 01-02-20            | o6301020 | 2923         | 8.09|
|        | 01-02-20            | o6301030 | 2923         | 7.92|
| SU Aur | 01-02-24            | o6305010 | 2383         | 5.04|
|        | 01-02-24            | o6305020 | 2940         | 4.21|
|        | 11-03-25            | ob6bb1030| 1489.2       | 2.33|
| SZ 102 | 11-05-29            | ob6b9030 | 1469.2       | 3.12|
| T Tau  | 01-02-21            | o6302010 | 2331         | 12.57|
|        | 01-02-21            | o6302020 | 2880         | 13.95|
|        | 01-02-22            | o6302030 | 2880         | 13.53|
| TW Hya | 00-05-07            | o59d01020| 1675.2       | 21.23|
| TWA 3A | 11-03-26            | ob6b22030| 1107.2       | 6.70|
| UX Tau | 11-11-10            | ob6b54030| 1408.2       | 2.35|
| V836 Tau | 11-02-05          | ob6ba6030| 1396.2       | 0.64|

Table 1. Log of observations.
Figure 1. The CII multiplet in the TTSs; only profiles with S/N > 2 are plotted. The fluxes are in units of $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Dashed lines mark the rest wavelengths of the CII transitions. For stars with multiple observations, the spectrum with the best S/N is shown.

In Fig. 2, the main spectral features in the 2324–2336 Å range are indicated on the spectrum of TW Hya, the star with the best S/N in the sample. Note that the CII multiplet is resolved.

Additional relevant features in the range are:

(i) The FeII lines at 2328.11 and 2333.52 Å (3d$^6$(3D)4s - 3d$^6$(3D)4p). Note that the 2328.11 Å transition is blended with the CII lines in most spectra.

(ii) The FeII lines at 2332.02 and 2333.52 Å.

(iii) The SiII multiplet at 2329.23, 2335.12 and 2335.32 Å.

3 MEASURING THE PLASMA PROPERTIES

CII, FeII and SiII features are intercombination transitions with very small Einstein coefficients and thus, optically thin tracers of the radiating plasma, suitable to be used to measure directly their properties. This characteristic was already noticed by Stencel et al. (1981) for CII lines, who proposed to use them as electron density tracers in the $10^7 \leq n_e \leq 10^{10.5}$ cm$^{-3}$ range in nebulae research.

In Fig. 3, we display the sensitivity of the line ratios to $T_e$ and $n_e$ for this quintuplet.

The plot was made by using the Atomic Database for Spectroscopic Diagnostics of Astrophysical Plasmas CHIANTI$^2$ (Dere et al. 1997; Landi et al. 2013). Note that below $n_e \leq 10^8$ cm$^{-3}$, the ratios are insensitive to the electron density except for very diffuse plasmas with $n_e \lesssim 10^{2.5}$ cm$^{-3}$. Therefore, other species need to be considered to constrain the $T_e$ of the plasma and the density for $n_e \gtrsim 10^{10.5}$ cm$^{-3}$ and $n_e \lesssim 10^9$ cm$^{-3}$. The FeII ratios are sensitive to the electron density for $n_e \gtrsim 10^9$ cm$^{-3}$ (see top panel in Fig. 4), the range of densities for which the CII quintuplet ratios are nearly constant. The SiII ratios are more sensitive to the temperature, particularly for $T_e \lesssim 10^{4.5}$ K (see bottom panel in Fig. 4). The combined analysis of all these ratios yields enough information to determine unambiguously the physical properties of the region where the lines are formed.

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Figure 2. Line identification in the spectral range 2320–2340 Å on TW Hya spectrum.

Figure 3. Emissivity ratios of the C\textsc{ii}] lines relative to the 2326.11 Å line, as a function of electron density. The labels 0, 1, 2, 3 and 4 correspond to the C\textsc{ii}] lines 2324, 2325, 2326, 2327 and 2328 Å, respectively. Solid, dashed and dotted lines correspond to temperatures of $T_e = 10^4$, $10^4.5$ and $10^5$ K, respectively.

For the calculations, we have assumed that all the lines are optically thin and formed via collisional excitation in a single plasma characterized by a pair ($n_e, T_e$). CHIANTI provides the ion emissivities (erg s$^{-1}$ cm$^{-3}$):

$$\epsilon_{ij} = \Delta E n_j(X\textsc{ii}) n(X\textsc{ii}) n(H) n_e^{-1} A_{ij},$$

where $n_j(X\textsc{ii})$ is the number density of the species $X\textsc{ii}$ in the upper level $(j)$, $n(X\textsc{ii})/n(H)$ is the ionization fraction of $X$ and $n(H)/n_e=0.83$ has been used since $T_e > 10^4$ K (see CHIANTI manual).

3.1 The numerical method

Making use of the emissivities from CHIANTI, we have computed the flux ratios relative to the C\textsc{ii}] (2326.11 Å) line of the following lines: C\textsc{ii}] (2324.21, 2325.4, 2327.64 and 2328.83 Å), Fe\textsc{ii}] (2328.11 and 2333.52 Å), Fe\textsc{ii}] (2332.02 Å) and Si\textsc{ii}] (2329.23, 2335.12 and 2335.32 Å), for a grid of electron temperatures and densities. The grid covers the range $4.0 \leq \log T_e(K) \leq 5.5$ and $0.0 \leq \log n_e(\text{cm}^{-3}) \leq 14.5$ with resolutions 0.025 dex in $\log(T_e)$ and 0.25 dex in $\log(n_e)$. We have assumed that the line profiles are adequately reproduced by Gaussian functions. In this manner, we have built a grid of simulated spectra in the 2323–2338 Å spectral range given by

$$F(\lambda) = F_0 \sum_{i=0}^{10} R_i \exp \left( \frac{-(\lambda - (\lambda_i + \delta))^2}{2\sigma^2} \right) + F_{\text{cont}},$$

where $n_j(X\textsc{ii})$ is the number density of the species $X\textsc{ii}$ in the upper level $(j)$, $n(X\textsc{ii})/n(H)$ is the ionization fraction of $X$ and $n(H)/n_e=0.83$ has been used since $T_e > 10^4$ K (see CHIANTI manual).
Figure 5. $\chi^2$ surfaces and contours for TW Hya (on the left) and DE Tau (on the right). At the bottom of the figures, we projected five $\chi^2$ contours starting close to the best solution $\chi^2_{\text{opt}}$ (0.08 and 0.48, respectively), with steps of 0.01. The black point at the bottom indicates the $T_e$ and $n_e$ values finally adopted.

where $F_0$ is the peak flux of the reference line (C II]2326), $R_i = F_i/F_0$ is the flux ratio between the peak of the $i$th line and $F_0$, $\sigma$ is the standard deviation of the Gaussian functions and $\lambda_i$ is the central wavelength of the $i$th emission line (which can be shifted $\delta \AA$ from its expected position). $F_{\text{cont}}$ is directly computed from the observations as the average flux in the 2320–2323 $\AA$ range for each spectrum; this is a featureless window (see Fig. 1). Both dispersion ($\sigma$) and shift ($\delta$) are assumed to be the same for all lines.

We developed an IDL based code to identify the synthetic spectrum that best fit the data consisting in two main steps. First, for each synthetic spectrum — defined by a pair ($n_e, T_e$) — the best fit to the data is found by a least squares scheme that leaves $F_0$, $\delta$ and $\sigma$ as free parameters for the fit. As a result, for any given model $i$ ($n_e, T_e$, $\sigma$), the set of parameters that best fit the data ($F_{0,i}, \sigma_i, \delta_i$), as well as the residuals, $\chi^2_i$, are computed. This allows plotting the $\chi^2$ surface in the ($n_e, T_e$) space (see Fig. 5). Then, the minimum of the surface is identified providing the ($n_e, T_e$) pair that best fit the data. This minimum corresponds to the optimal fit, i.e. $\chi^2_{\text{opt}} = \min(\chi^2_i)$.

In Table 2, the $n_e$, $T_e$, $\sigma$, $\delta$ values corresponding to the best-fitting model are provided for all the TT Ser in the initial condition. For the free parameters are set as follows: $\sigma = 0.1 \AA$ (approximately equivalent to the combination of the spectral resolution obtained with STIS/E230M and thermal broadening), $F_0$ is set as the peak flux around 2326 $\AA$ and $\delta$ is such that $F(2326.11 - \delta) = F_0$ in the observed spectrum. We performed several tests to check the dependence of the results on the initial values of the free parameters. By varying these initial values, the final solution ($\chi^2_{\text{opt}}$) never differed by more than one step in the grid of $T_e$ and $n_e$ values. This means that the steps of the grid represent the internal precision of the fitting procedure ($\delta \log T_e \approx 0.025$ and $\delta \log n_e (\text{cm}^{-3}) \approx 0.25$); they are the same for all stars in the sample.

From the fitting procedure, we also estimated the uncertainties associated to $\delta$, $\sigma$ and each line flux. For this, we selected the eight closest grid points to the best fit (the local minimum) and we calculated the standard deviation from the average value using these eight points. The standard deviations in $\delta$ is always $\lesssim 5 \text{ km s}^{-1}$, whereas in $\sigma$ is $\lesssim 6 \text{ km s}^{-1}$. These uncertainties are not provided in Table 2 because they are negligible. The final simulated fluxes with their associated errors are shown in Table 3.

The Fe II]2322.02 line has not been considered for the fit. We have found a large discrepancy between CHIANTI predictions for the line strength ($\epsilon(2332.02) \sim 0.06 \epsilon(2333.52)$) and the observations, where both Fe II lines have comparable strengths (see Fig. 2).

Fig. 6 shows two illustrative examples of the results of the fitting procedure. The targets selected are TW Hya, with high S/N and DE Tau with low S/N. The difference in S/N is readily observed in the $\chi^2$ surface (see Fig. 5); the height of the surface above the ($n_e, T_e$) plane increases as the S/N decreases. However, both surfaces share some common characteristics: (1) a steep rise of the $\chi^2$ surface towards low $T_e$ and low $n_e$ and (2) there is always a narrow range of ($n_e, T_e$) that gives the best statistical fits to the original data (see the projected contours of the $\chi^2$ surfaces on the $n_e, T_e$ plane in Fig. 5).

3.2 ($n_e, T_e$) in the line emission region

Fig. 7 shows the electron densities and temperatures corresponding to the optimal fits. For stars with multiple observations, only the best-fitting (with the minimum $\chi^2_{\text{opt}}$) results are plotted. The differences among observations are small having very similar results in most of the cases (see Table 2).

Most sources are grouped in a region with 4.1 $\lesssim \log(T_e) \lesssim 4.5$ and 8 $\lesssim \log(n_e) \lesssim 12$. There are three stars outside this region: DR Tau, AA Tau and SZ 102. DR Tau converged to values lying very close to the limits of the $n_e - T_e$ grid. In the case of SZ 102, the low density probably indicates that the C II emission is dominated by an extended ionized envelope. Something similar might be occurring in AA Tau, a CTTS with a warped disc (Ménard et al. 2003) that displays very peculiar profiles in the UV emission lines (France et al. 2012; Ardila et al. 2013; Gómez de Castro 2013b). These three stars are represented in the figure as filled circles. These ‘unusual’ values lead us to think that maybe the C II, Fe II and Si II lines are not formed under the same physical conditions as the other sources. Therefore, these three stars are excluded from the following analysis.

3.3 Consistency tests

For this purpose, we have compared the observed flux in the C II] feature with the flux derived from the best-fitting model for each target — including the C II] quintuplet and the unresolved Fe II]2328.1 and Si II]2328.23 lines.

The observed flux has been measured in the range 2324–2330 $\AA$ as: $F_{\text{obs}} = (f - N_{\text{pix}} F_{\text{cont}}) A \lambda$, where $F_{\text{cont}}$ is the continuum average flux, $N_{\text{pix}}$ is the number of pixels in the selected window (151 pixels), $f$ is the wavelength-integrated line flux and $A \lambda$ the step in wavelength (0.04 $\AA$). We also estimated the corresponding flux error using $\delta F = N_{\text{pix}} A \lambda \sigma_{\text{cont}}$ (being $\sigma_{\text{cont}}$ the dispersion around this average). The continuum was measured in the 2320–2323 $\AA$ spectral range.

The simulated flux of each line has been calculated as the integral of the Gaussian function fitting that line. Table 3 shows the fluxes for each line. The total flux of the C II] quintuplet has been calculated from the best-fitting models as

$$F_{\text{sim}}(\text{C II}) = \sigma \sqrt{2 \pi} F_0 \sum_{i=0}^{4} R_i. \tag{2}$$

The Si II]2313 flux is the sum of the components at 2335.12 and 2335.52 $\AA$ since they are not resolved in the HST/STIS spectra. The comparison between observed and fitted line is shown in Fig. 8. Most of the observed fluxes are slightly higher than the
simulated ones but the discrepancy is well within the expected value given the S/N of the data. TW Hya shows the largest discrepancy that we interpret as a result of the simplicity of the modelling, i.e. the difficulties to fit the data to a ‘single plasma’ emission. In this sense, we would like to remark that the $(n_e, T_e)$ values in Table 2 should be understood as average values on the plasma emission region.

We have also calculated the contribution of the Fe II $\lambda$2328 and Si II $\lambda$2329 fluxes to the 2326 Å feature, unresolved in most of the TTs spectra. From the simulated spectra, we have found that Fe II $\lambda$2328 emission can account for up to $\sim 15$ per cent of the flux, whereas Si II $\lambda$2329 contribution is negligible ($\lesssim 0.5$ per cent).

### 3.3.1 Line ratios as $T_e$ and $n_e$ indicators

The C II/[Si II] flux ratio is a sensitive tracer of the electron temperature in the range of interest. As it is shown in Fig. 9, $T_e$ is basically derived from this ratio in our code. The regression line in Fig. 9 has a Pearson’s coefficient of $r = 0.91$ with a $p$–value$^3 = 4.8 \times 10^{-7}$. The regression equation is

$$ \log(F(\text{C II})/F(\text{Si II})) = (2.1 \pm 0.3) \log(T_e) - (8.1 \pm 1.1). $$

We have not found any significant correlation between C II/Fe II $\lambda$2313 flux ratio and the temperature.

Regarding electron density, we have recovered the expected relation between $n_e$ and the C II/Fe II $\lambda$2313 and Si II/Fe II $\lambda$2313 ratios. The regression parameters are

(i) For C II/Fe II $\lambda$2313: $r \approx -0.6$ and $p$–value = 0.015

(ii) For Si II/Fe II $\lambda$2313: $r \approx -0.9$, $p$–value = 8.34 $\times 10^{-7}$ and regression equation: $\log(F(\text{Si II})/F(\text{Fe II})) = (-0.25 \pm 0.03) \log(n_e) + (3.02 \pm 0.32)$, as shown in Fig. 10.

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### Table 2. Physical parameters derived from the fitting.

| Star     | Data set | log($T_e$) (K) | log($n_e$) (cm$^{-3}$) | $\chi^2_{\text{opt}}$ | $\delta$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | $F_0$ (erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$) |
|----------|----------|----------------|------------------------|-----------------------|------------------------|------------------------|---------------------------------|
| AA Tau   | ob6ba7030| 4.95           | 9.50                   | 0.54                  | 17.67                  | 40.88                  | 6.70 $\times 10^{-14}$          |
| CV Cha   | ob6b18020| 4.10           | 10.50                  | 0.28                  | 18.57                  | 82.03                  | 1.82 $\times 10^{-14}$          |
| CY Tau   | o5c03020 | 4.50           | 11.75                  | 0.49                  | 15.22                  | 23.73                  | 6.08 $\times 10^{-14}$          |
| DE Tau   | ob6ba8030| 4.15           | 10.00                  | 0.48                  | 0.90                   | 56.36                  | 3.52 $\times 10^{-14}$          |
| DF Tau   | o5c0102  | 4.45           | 11.50                  | 0.01                  | 9.29                   | 66.42                  | 1.12 $\times 10^{-13}$          |
| DG Tau   | o6303020 | 4.18           | 10.25                  | 0.12                  | $-67.32$               | 104.72                 | 9.23 $\times 10^{-15}$          |
| DR Tau   | o63004010| 5.48           | 13.75                  | 0.42                  | $-24.76$               | 85.38                  | 1.62 $\times 10^{-14}$          |
| DS Tau   | o5c0102  | 4.35           | 9.75                   | 0.75                  | 27.34                  | 62.03                  | 3.72 $\times 10^{-14}$          |
| SU Aur   | o6305010 | 4.33           | 11.00                  | 0.18                  | 18.70                  | 61.00                  | 4.31 $\times 10^{-14}$          |
| T Tau    | o6302010 | 4.15           | 10.50                  | 0.01                  | 3.87                   | 61.52                  | 9.15 $\times 10^{-14}$          |
| TWHya    | o59d01020| 4.50           | 12.25                  | 0.07                  | 15.99                  | 66.03                  | 1.74 $\times 10^{-14}$          |
| TWA3A    | ob6b22030| 4.28           | 9.25                   | 0.62                  | 17.28                  | 49.52                  | 7.19 $\times 10^{-13}$          |
| UX Tau   | ob6b54030| 4.40           | 8.75                   | 0.32                  | 23.34                  | 35.72                  | 3.10 $\times 10^{-14}$          |
Table 3. Fluxes of the main features derived from the fitting procedure. *(a)*

| Star     | Data set     | Flux(C ii]) | Flux(Fe ii]2328) | Flux(Si ii]2329) | Flux(Fe ii]2331) | Flux(Si ii]2335) |
|----------|--------------|-------------|------------------|------------------|------------------|------------------|
| AA Tau   | ob6ba7030    | (9.02 ± 0.17) × 10^{-14} | (2.58 ± 1.12) × 10^{-20} | (4.59 ± 1.42) × 10^{-18} | (7.47 ± 3.22) × 10^{-20} | (4.45 ± 1.42) × 10^{-16} |
| CV Cha   | ob6ba8020    | (4.84 ± 1.02) × 10^{-14} | (5.09 ± 1.50) × 10^{-15} | (1.99 ± 0.36) × 10^{-16} | (1.46 ± 0.43) × 10^{-14} | (3.52 ± 0.59) × 10^{-14} |
| CY Tau   | o5c0302      | (4.73 ± 0.03) × 10^{-14} | (6.36 ± 4.02) × 10^{-16} | (1.52 ± 0.22) × 10^{-17} | (1.81 ± 1.14) × 10^{-15} | (3.16 ± 0.46) × 10^{-15} |
| DE Tau   | o6ba8030     | (6.73 ± 0.29) × 10^{-14} | (1.82 ± 0.50) × 10^{-15} | (1.30 ± 0.26) × 10^{-16} | (5.21 ± 1.44) × 10^{-15} | (1.86 ± 0.38) × 10^{-14} |
| DF Tau   | o5ck0102     | (2.43 ± 0.03) × 10^{-13} | (3.75 ± 2.34) × 10^{-15} | (1.09 ± 0.17) × 10^{-16} | (1.07 ± 0.67) × 10^{-14} | (2.24 ± 0.35) × 10^{-14} |
| DG Tau   | o63i03020    | (3.13 ± 0.09) × 10^{-14} | (8.78 ± 2.52) × 10^{-16} | (5.03 ± 0.70) × 10^{-17} | (2.51 ± 0.72) × 10^{-15} | (8.03 ± 1.26) × 10^{-15} |
| DR Tau   | o63i04010    | (4.53 ± 0.01) × 10^{-14} | (3.39 ± 2.17) × 10^{-19} | (2.18 ± 0.13) × 10^{-17} | (9.94 ± 8.36) × 10^{-20} | (4.63 ± 0.27) × 10^{-15} |
| FS Ori   | o63i04020    | (4.76 ± 0.00) × 10^{-14} | (3.56 ± 2.28) × 10^{-19} | (2.29 ± 0.14) × 10^{-17} | (1.05 ± 0.67) × 10^{-18} | (4.87 ± 0.29) × 10^{-15} |
| GM Aur   | o6ba61030    | (7.32 ± 0.29) × 10^{-14} | (3.31 ± 1.84) × 10^{-15} | (6.24 ± 0.79) × 10^{-17} | (1.06 ± 0.32) × 10^{-15} | (7.58 ± 0.98) × 10^{-15} |
| PDS66    | o6ba23030    | (2.85 ± 0.06) × 10^{-13} | (2.00 ± 0.37) × 10^{-15} | (3.59 ± 0.33) × 10^{-16} | (5.68 ± 1.06) × 10^{-15} | (3.15 ± 0.27) × 10^{-14} |
| RECX15   | o6ba7030     | (8.39 ± 0.22) × 10^{-14} | (1.60 ± 0.37) × 10^{-15} | (2.19 ± 0.46) × 10^{-16} | (4.57 ± 1.07) × 10^{-15} | (1.88 ± 0.39) × 10^{-14} |
| RECX11   | o6ba4030     | (9.06 ± 0.13) × 10^{-14} | (1.87 ± 0.59) × 10^{-15} | (6.39 ± 0.07) × 10^{-17} | (5.26 ± 1.70) × 10^{-15} | (5.83 ± 0.88) × 10^{-15} |
| RY Tau   | o63i01010    | (9.20 ± 0.50) × 10^{-14} | (2.43 ± 0.69) × 10^{-15} | (3.25 ± 0.84) × 10^{-16} | (6.96 ± 2.00) × 10^{-15} | (2.78 ± 0.72) × 10^{-14} |
| SU Aur   | o63i03010    | (8.65 ± 0.52) × 10^{-14} | (4.84 ± 1.79) × 10^{-15} | (4.68 ± 1.06) × 10^{-16} | (1.38 ± 0.51) × 10^{-14} | (2.74 ± 0.36) × 10^{-14} |
| SZ102    | o6ba9030     | (5.97 ± 0.08) × 10^{-14} | (2.02 ± 0.67) × 10^{-18} | (3.67 ± 0.60) × 10^{-17} | (1.44 ± 0.47) × 10^{-17} | (1.94 ± 0.32) × 10^{-15} |
| T Tau    | o63i02010    | (1.83 ± 0.13) × 10^{-13} | (8.89 ± 3.09) × 10^{-15} | (3.70 ± 0.64) × 10^{-16} | (2.55 ± 0.89) × 10^{-14} | (6.49 ± 1.18) × 10^{-14} |
| TW Hya   | o63i02020    | (1.78 ± 0.20) × 10^{-13} | (8.89 ± 2.72) × 10^{-15} | (4.81 ± 0.99) × 10^{-16} | (2.55 ± 0.78) × 10^{-14} | (7.75 ± 1.58) × 10^{-14} |
| UX Tau   | o6ba54030    | (3.94 ± 0.07) × 10^{-14} | (7.86 ± 2.54) × 10^{-17} | (2.83 ± 0.43) × 10^{-17} | (2.23 ± 0.72) × 10^{-16} | (2.47 ± 0.37) × 10^{-15} |

*(a)*Fluxes are not extinction corrected.

### 4 C II AS AN ACCRETION TRACER

The C ii] quintuplet have been found to be a good tracer of the accretion rate (Calvet et al. 2004; Ingleby et al. 2013). In this section, we discuss this point as well as the relationship between the obtained results, (n_e, T_e, σ) and accretion rate (Ṁ).

#### 4.1 Dispersion versus electron temperature

Further insight on the source of the profile broadening can be drawn from Fig. 11. The line dispersions that best fit the observed spectra are shown in Table 2 and they are in the range 20 < σ < 160 km s^{-1}. TW Hya and CY Tau have σ < 25 km s^{-1} and high T_e values (log T_e(K) ≈ 4.4 – 4.5). For these stars the line broadening is consistent with thermal broadening (v_0 ∼ 20 km s^{-1}). SU Aur is the source with the largest line broadening, σ > 100 km s^{-1}, and a temperature of T_e ≥ 10^4 K. This star is the fastest rotator in the sample (v sin i ∼ 60 km s^{-1}) thus, rotation could be an important source of line broadening. The rest of the stars have intermediate σ values (40 < σ < 100 km s^{-1}) and temperatures in the range log T_e(K) ≈ 4.1 – 4.45. The dispersions are suprathermal and the contribution of rotational broadening is negligible since with v sin i values are in the range ∼5 – 25 km s^{-1} (see Table 4). There is a mild correlation between σ and T_e, as shown in Fig. 11 (r = −0.6 and a p-value = 0.018).

#### 4.2 Dispersion versus accretion rate

We have also examined the relation between dispersion, σ and accretion rate, Ṁ. As shown in Fig. 12, TTSs show a statistically significant correlation between σ and Ṁ: the higher the accretion rate the wider the line. Note that there is a small group of TTSs (TWA 3A, RECX 11, RECX 15 and PDS 66) with Ṁ < 10^{-9} M⊙ yr^{-1}, that seem to have too low accretion rates for the given dispersion. PDS 66 also displays an unusually high C ii] flux for the accretion rate derived by Ingleby et al. (2013). For this reason these stars have not been considered to determine the correlation coefficient. The Pearson’s coefficient is r = 0.87 with a p-value = 0.0002. This trend suggests a clear connection between the region in which
Figure 6. Original spectra (solid lines) and their best fits (dotted lines) for two example stars: TW Hya (top) and DE Tau (bottom).

Figure 7. Electron densities \( (n_e \text{ in cm}^{-3}) \) and temperatures \( (T_e \text{ in K}) \) corresponding to the best fit to the observed spectra for the stars in the sample. Circle radius corresponds to the uncertainties associated with \( n_e \) and \( T_e \). Filled circles indicate stars with values out of the range where most of the sources in the sample are present.

Figure 8. The observed flux in the 2326 Å feature compared with the derived from the best fit. Dashed line marks the 1:1 relation.

Figure 9. The ratio between C\textsc{II} and Si\textsc{II} fluxes \( F(\text{C}\textsc{II})/F(\text{Si}\textsc{II}) \) as a function of the temperature \( T_e \) (K). Solid line is the best linear fit.

Figure 10. \( F(\text{Si}\textsc{II})/F(\text{Fe}\textsc{II}) \) as a function of the electron density \( n_e \) (cm\(^{-3}\)). Solid line represents the best linear fit.
The C II UV feature in TTSs

4.3 C II] luminosity versus accretion rate

Here, we re-examine the correlation reported by Ingleby et al. (2013) from low-dispersion data between the accretion rate/luminosity and the C II] flux. Fluxes are extinction corrected according to Valencic, Clayton & Gordon (2004) assuming $R_V = 3.1$ (see Table 4 for a compilation of the $A_V$ values and distances used in the calculation, as well as other relevant parameters). The extinction $A_V$ is one of the major sources of uncertainty affecting, among other things, the accretion rate estimates. For this reason, extinctions have been selected mainly from the same source than the accretion rates (Ingleby et al. 2013). As a test, we have repeated the analysis with data from Ardila et al. (2013), and found the same general trend. As shown in Fig. 13, the C II] luminosity increases as the accretion rate does:

$$\log \left( \frac{L(C II)}{L_\odot} \right) = (1.24 \pm 0.26) \log \dot{M} + (6.27 \pm 2.06)$$ (4)

4.4 Electron density versus accretion rate

In Fig. 14, we have plotted the electron density as a function of the accretion rate. TWA 3A, RECX 11, RECX 15 and PDS 66 have again a peculiar behaviour related with their, apparently, too low accretion rates when compared with the observed electron density in the emission region. There are four stars (TW Hya, CY Tau, GM Aur and DF Tau) with $n_e > 10^{11}$ cm$^{-3}$. There seems to be a trend for $n_e$ to increase as the accretion rate does it ($r = 0.92$ and a $p$-value = 0.001) in sources with $n_e \lesssim 10^{11}$ cm$^{-3}$ and $\dot{M} > 10^{-8}$ (M$\odot$ yr$^{-1}$).

4.5 Blueshifted profiles

The shift of the lines, $\delta$, obtained from the fitting, was corrected to the stellar rest frame and it is provided in Table 2; the radial velocities of the TTSs are compiled in Table 4. Note that the pointing errors in the STIS data result in a velocity uncertainty of 3 km s$^{-1}$.
negligible for the purpose of this work. Most TTSs satisfy $-20 \leq \delta \leq 20$ km s$^{-1}$; however, there are three stars namely, DG Tau, FU Ori and RY Tau with clearly blueshifted emission at velocities of $-81.5$, $-73.5$ and $-47.1$ km s$^{-1}$, respectively. This blueshift indicates a contribution from the unresolved base of the jet.

5 CONCLUSIONS

In this work, we have studied the semiforbidden lines of C II, Si II and Fe II in the 2310–2340 Å spectral range for a sample of 20 TTSs using 30 medium-resolution spectra obtained with HST/STIS instrument.

As the lines are blended in a broad feature in most sources, we have developed a numerical method to determine the properties of the line emission region assuming that the radiating plasma can be characterized by a single $T_e$ and $n_e$ pair, considering solar abundances. This is the first work where $n_e$ and $T_e$ has been determined for such a large sample of TTSs; previous works dealt with much smaller samples (Gómez de Castro & Verdugo 2001, 2003).

In magnetospheric accretion, matter flows from the inner border of the circumstellar disc on the magnetospheric surface to finally fall on to the star. Near the stellar surface a dense and hot shock is formed producing hot spots. The sheared magnetosphere-disc boundary layer is expected to be very prone to the development of turbulent flows.

Within this overall picture there are four issues worth remarking.

(i) In most TTSs, the C II, Si II and Fe II radiation seems to be produced in an extended magnetospheric structure characterized by $10^{8} \leq n_e \leq 10^{12}$ cm$^{-3}$ and $10^{4} \leq T_e \leq 10^{5.5}$ K. The line broadening is suprathermal except for two stars (TW Hya and CY Tau).

(ii) There are three sources, DG Tau, FU Ori and RY Tau with blueshifted lines centroid. DG Tau and RY Tau have resolved jets and FU Ori has a strong wind. The large blueshifted velocities in these stars can be due to the contribution of the outflows to the C II lines, suggesting that the properties in the base of the outflow are similar to those in the base of the accretion stream. The electron densities of the jet sources derived from the C II, Si II and Fe II lines agree well with previous estimates of electron densities at the base of the jet (Gómez de Castro & Verdugo 2001, 2003, 2007). The observations agree with the predictions of hot disc winds (Gómez de Castro & Ferro-Fontán 2005). From the theoretical point of view, it is expected that both, the base of the jet and the foot-point of the accretion flow, share similar physical conditions (see e.g. Mohanty & Shu 2008).

Table 4. Properties of the sample taken from the literature.

| Star   | SpT   | $L$ (L$_\odot$) | $R$ (R$_\odot$) | $M$ (M$_\odot$) | $d$ (pc) | log $(M)$ (M$_\odot$ yr$^{-1}$) | $v$ sin $i$ (km s$^{-1}$) | $A_V$ (mag) | $v_{\text{rad}}$ (km s$^{-1}$) | Ref. |
|--------|-------|---------------|----------------|---------------|--------|-----------------|----------------|-----------|----------------|------|
| AA Tau | K7    | 1             | 2.1            | 0.8           | 140    | $-7.82$         | 11              | 1         | 16.1          | 1,17 |
| CY Tau | M2    | 0.31          | 1.63           | 0.55          | 140    | $-8.86$         | 10.6            | 0.03      | 19.1          | 2,5,3,18 |
| CV Cha | G9    | 3.1           | 2              | 1.5           | 160    | $-7.23$         | 32              | 1.5       | 16.1          | 1,13,10 |
| DE Tau | M2    | 0.8           | 2.4            | 0.4           | 140    | $-7.55$         | 10              | 0.9       | 14.9          | 1,19 |
| DF Tau A | M1 | 0.56          | 3.37           | 0.68          | 140    | $-8$            | 16.1            | 0.15      | 11            | 2,7,3,9 |
| DG Tau | K6    | 1.1           | 1.88           | 140           | $-7.34$ | 20              | 1.41            | 15.4      | 2,7,10,18 |
| DR Tau | K5    | 0.4           | 1.1            | 0.9           | 140    | $-7.28$         | 10              | 1.4       | 27.6          | 1,3,10 |
| DS Tau | K5    | 0.68          | 1.36           | 1.04          | 140    | $-7.94$         | 10              | 0.9       | 16.3          | 2,7,17 |
| FU Ori | G0    | –             | –              | –             | 450    | –               | –               | –         | 28            | 15,19 |
| GM Aur | K7    | 1.2           | 2.3            | 0.8           | 140    | $-8.02$         | 12.4            | 0.6       | 15            | 1,9,17 |
| PDS66 | K1    | 0.9           | 1.3            | 1.1           | 86     | $-9.89$         | 14               | 0.2       | 11.6          | 1,13,14 |
| RECX15 | M3   | 0.1           | 0.9            | 0.3           | 97     | $-9.1$          | 15.9            | 0         | 15.9          | 1,13,13 |
| RECX11 | K5   | 0.6           | 1.4            | 1             | 97     | $-9.77$         | 16.4            | 0         | 18            | 1,13,12 |
| RY Tau | G1    | 9.6           | 2.9            | 2             | 140    | $-7.17$         | 48.7            | 2.2       | 16.5          | 7,17 |
| SU Aur | G1    | 7.8           | 2.6            | 1.7           | 140    | $-7.31$         | 59              | 0.9       | 16            | 7,18,17 |
| SUZ02 | K0    | –             | –              | 0.75          | 200    | $-8.1$          | 0.32            | 5         | 3.4           | 1,19 |
| T Tau | K0    | 7.29          | 2.9            | 2.1           | 140    | $-7.5$          | 20.1            | 1.46      | 19.1          | 2,8,17 |
| TW Hya | K7    | 0.3           | 1.1            | 0.8           | 56     | $-8.74$         | 5.8             | 0         | 13.5          | 1,3,16 |
| TWA3A | M3    | 0.4           | 1.8            | 0.3           | 50     | $-10$           | 12              | 0         | 0             | 1,14 |
| UX Tau | K5    | 0.91          | 2.05           | 1.0          | 140    | $-7.96$         | 25.4            | 0.26      | 15.6          | 2,3,6,11,17 |

(1) Ingleby et al. (2013); (2) White & Ghez (2001); (3) Ardila et al. (2013); (4) France et al. (2012); (5) Gullbring et al. (1998); (6) Andrews et al. (2011); (7) Salyk et al. (2013); (8) Calvet et al. (2004); (9) Clarke & Bouvier (2000); (10) Johns-Krull et al. (2000); (11) Preibisch & Smith (1997); (12) Jayawardhana et al. (2006); (13) Woitke et al. (2011); (14) da Silva et al. (2009); (15) Petrov & Herbig (2008); (16) Herczeg et al. (2006); (17) Hartmann et al. (1986); (18) Nguyen et al. (2012); (19) Malaroda, Levato & Gallianni (2006).
(iii) The C\textsc{ii} quintuplet can be used as a reliable tracer of the mass accretion rate on the star. C\textsc{ii} luminosity increases as the accretion rate does it in agreement with previous results by Calvet et al. (2004) and Ingleby et al. (2013).

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APPENDIX A: VARIABILITY OF THE C\textsc{ii} PROFILES

Significant variations in the C\textsc{ii} profiles are only found in DS Tau (see Fig. A1). In this section, we include the figures showing the variability of the C\textsc{ii} profiles in TTSs. Only observations with S/N > 2 are compared.
Figure A1. Variability of the CII profiles of the TTSs. For each star, the highest S/N observation is used as reference and is superimposed as red dotted line.