Accretion shocks in T Tauri stars. Diagnosis via semiforbidden UV lines ratios.

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ABSTRACT

Numerical calculations of the structure of accretion shocks in T Tauri stars (TTSs) indicate that the C III]1909, O III]1661+1666 and Si III]1892 ultraviolet lines should have comparable intensities. We show how the density and the velocity of the accreted gas can be derived from these lines ratios. We also indicate how these parameters can be used, together with other less reliable as the distance and the extinction, to derive the accretion rate and the accretion luminosity. It is shown that the lines ratios as well as their absolute fluxes (as measured with the International Ultraviolet Explorer) are in agreement with the predictions of the accretion shock model. However this method is best suited for the analysis of high resolution data (as those obtained with the Hubble Space Telescope) from which accurate fluxes can be determined and blended components (stellar atmosphere, winds) can also be properly substracted out.

Key words: stars: individual: DI Cep – stars: pre-main-sequence – stars: T Tauri

1 INTRODUCTION

T Tauri stars (TTSs) are accreting material from their surrounding disk. It is now widely assumed that the accretion disk does not reach the stellar surface and that henceforth, the matter falls onto the star at nearly free-fall speed. The kinetic energy of the infalling material is then released in the accretion shock at the point of impact. Numerical calculations of the structure and the spectrum of accretion shock waves have been carried out by Lamzin (1998). It follows from these calculations that semiforbidden lines of C III]$_{1909}$ and Si III]$_{1892}$ as well as O III]$_{1665}$ form before the shock front, where the infalling gas is ionized by the X-rays radiation generated in the hot (T$\sim 10^6$ K) post-shock region. By comparison, the regions of the accretion flow, studied by Hartmann et al. (1994), Martin (1996) and Muzerolle et al. (1998) are situated very far from the shock front, where gas temperature and ionizing radiation flux are too low to produce C^{++}, Si^{++} and O^{++} ions in significant amount.

The model predicts that these three lines should have comparable intensities in the TTSs spectra, so their flux ratio depends strongly on infall gas density and infall gas velocity. These lines are optically thin (for example, the optical depth of the C III]$_{1909}$ line is less than 0.02 for all models we have used) and have similar wavelengths. Henceforth their ratios are independent of the geometry of the accretion zone and moreover, they are only mildly affected by the large inaccuracies in the determination of the extinction towards

the TTSs. As a consequence they are an ideal tool for the diagnostic of the accretion shocks.

In this letter we compare the results of our calculations with observational data from the Final Archive of the International Ultraviolet Explorer (IUE) satellite. In Sect. 2 we show that the expected fluxes (at the Earth) of the C III]$_{1909}$, Si III]$_{1892}$ and O III]$_{1665}$ lines for the nearby TTSs are of $\sim 10^{-13} - 10^{-14}$ erg s^{-1} cm^{-2}; these fluxes are susceptible to be measured with the IUE (see e.g. Gómez de Castro & Franqueira, 1997 (hereafter GF) for a compilation). In Sect. 3 we present the results of a search on the IUE Final Archive and identify some TTSs for which C III]$_{1909}$, Si III]$_{1892}$ and O III]$_{1665}$ lines are detected. These stars are represented in a Si III]/OIII] vs Si III]/C III] diagram in Sect. 4; we show that the lines ratios observed in the TTSs are compatible with the predictions of the accretion shock model for a reasonable range of infalling gas density and velocity. We illustrate how these parameters can be used (together with other less reliable as the distance and the extinction) to derive the accretion rate for a sample star (DI Cep). Finally in Sect. 5 we describe the limitations of the method when applied to low spectral resolution data.

2 MODEL PREDICTIONS FOR THE LINES INTENSITY

Accretion shock wave has been considered as plane parallel (i.e. 1-D) and stationary in Eulerian coordinates. We
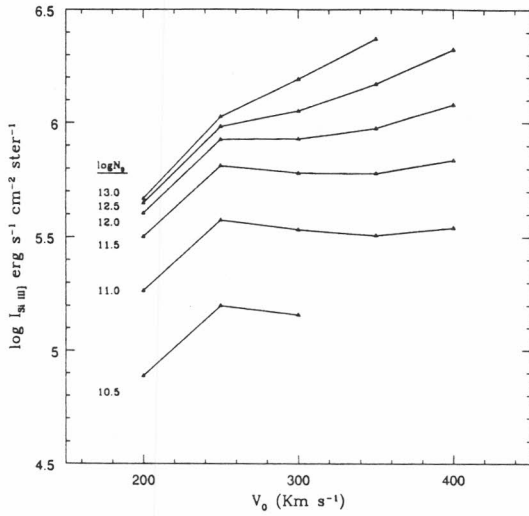
Figure 1. Expected intensity of the Si III]$_{1892}$ line as a function of the infall gas velocity V_0 for different values of the infall gas density N_0.

have computed the lines fluxes for a broad range of infall velocities ($200 \leq V_0(\mathrm{Km\,s^{-1}}) \leq 400$) and gas densities ($10.5 \leq \log N_0(\mathrm{cm^{-3}}) \leq 13$. This range has been defined so it satisfies the physical assumptions made to simplify the general system of radiative hydrodynamic equations (see Lamzin 1995,1998 for details).

Semiforbidden lines of C III]$_{1909}$, Si III]$_{1892}$ and O III]$_{1665}$ are found to be formed via electron collisional excitation before the shock front in the region with gas temperature 15.000-20.000 K; this implies that the critical densities are 3.4×10^{10}, 1.5×10^{11} and 1.5×10^{12} cm^{-3} for the O III]$_{1665}$, C III]$_{1909}$ and Si III]$_{1892}$ lines respectively (see CHIANTI database (http://wwwsolar.nrl.navy.mil/chianti.html)). Notice that the O III]$_{1665}$ line is a doublet with components at $\lambda\lambda$ 1660.802 Å, and 1666.156 Å, which originate under transitions from the level $2s\,2p^3\,^5S_2$ to the term $2s^2\,2p^2\,^3P$ with $J = 1$ and $J = 2$ respectively. The components of the doublet should have an intensity ratio $\simeq 1 : 3$, equal to the ratio of their transition probabilities (145 and 426 s^{-1}).

If $\varepsilon(\mathrm{erg/s/cm^3})$ is the emissivity of an optically thin line then its intensity $I^n(\mathrm{erg/s/cm^2/ster})$ in the direction, perpendicular to the shock front is equal to $I^n = 1/4\pi \cdot \int \varepsilon \mathrm{d}z$. The shock models of Lamzin (1998) provide tabulations of I^n as functions of N_0 and V_0. As an example we represent in Fig. 1 the intensity of the Si III]$_{1892}$ line as a function of the infall gas velocity for different values of the infall gas density.

Then the observed flux F at the Earth can be expressed as:

$$F = \frac{I^n S_{ac}}{d^2} \exp(-0.92 A_\lambda), \qquad (1)$$

where S_{ac} is the *visible* surface of the accretion zone; d is the distance to the star and A_λ is the interstellar extinction at wavelength λ. Notice that the line flux depends on the

fraction of the stellar surface covered by an accretion shock, but not on the detailed geometry of the accretion zone; the result is valid for optically thin lines only.

As an example, the expected flux (erg/s/cm^2) from an accretion shock with parameters $\log N_0 = 11.5$ and $V_0 = 300$ km s^{-1}, which covers a 10% of the visible stellar hemisphere is:

$$F = 1.6 \times 10^{-14} \left(\frac{R_*}{R_\odot}\right)^2 \left(\frac{d}{100\mathrm{pc}}\right)^{-2} \exp(-0.92 A_\lambda)$$

Line fluxes in the range $10^{-13} - 10^{-14}$ erg s^{-1} cm^{-2} are susceptible to be detected with the IUE satellite. Therefore, to test this diagnosis method we have searched the IUE Final Archive to find all the TTSs observed in the 1200 – 2000 Å spectral range. Previous works have already reported the detection of C III]$_{1909}$ and Si III]$_{1892}$ lines (see Gómez de Castro, 1998 for an up-to-date review).

3 THE IUE DATA

The sample of TTS observed with the IUE has been studied in detail by GF. The subset of TTS observed in the short wavelength range (1200-2000 Å) consist of 27 stars. A detailed list with image numbers, dates of observation and other useful parameters can be found in GF. The spectra have been processed at VILSPA with the New IUE Spectral Image Processing System (NEWSIPS) extraction for point sources. A detailed comparison of the effect of the extraction system on the line fluxes derived for the TTSs can be found in Huélamo et al (1998).

There are only some few TTSs for which at least two of the three lines are detected within the sensitivity threshold of IUE. These stars as well as the derived line fluxes are given in Table 1. The line fluxes have been measured on an average spectrum obtained by co-adding the best quality spectra (spectra with S/N $\geq$ 3 in the relevant lines). Some examples are displayed in Fig.2. We have tentatively identified the feature at 1665 Å as the O III]$_{1665}$ doublet but high resolution spectra are required to confirm this identification since there are nearby lines of C I(UV2, λ1657) and Al II (UV2, λ1671) which may be strong in the TTSs. Note also that there is a Reseau Mark for the geometric calibration of the IUE camera longwards shifted of the C III]$_{1909}$ line which may introduce further inaccuracies in the determination of the C III]$_{1909}$ fluxes for some stars. High resolution spectra are henceforth instrumental for a full-proof application of the method outlined in this work (they will allow confirming the line identification as well as measuring accurate fluxes by substracting out the possible contribution of nearby lines).

4 THE Si III]/OIII] VS. Si III]/C III] DIAGRAM

Let us assume that the parameters of the infalling gas (density and velocity) are the same over all the accretion zone (homogenous accretion). Then one can derive from Eq.(1) that the ratio between the intensities of two lines at the outer boundary of the shock wave is equal to the ratio of their de-reddened observed fluxes:

$$\frac{I_2^n}{I_1^n} = \frac{F_2}{F_1} \exp[0.92\,(A_{\lambda 2} - A_{\lambda 1})]. \qquad (2)$$
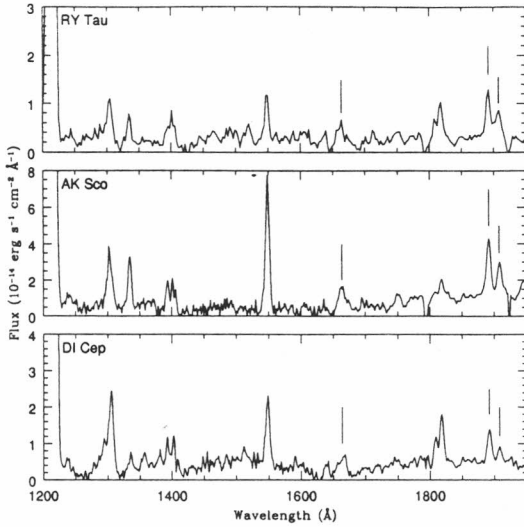
Figure 2. UV spectrum in the 1200 – 1950 Å range for RY Tau, AK Sco and DI Cep. The spectra displayed correspond to the average of all the observations available in the IUE Final Archive. The position of the O III]$_{1665}$, Si III]$_{1892}$ and C III]$_{1909}$ lines is marked in the three spectra.

Table 1. IUE Data

HBC	Star Name	$F_{OIII]}$ $10^{-13}\frac{erg}{scm^2}$	$F_{SiIII]}$ $10^{-13}\frac{erg}{scm^2}$	$F_{CIII]}$ $10^{-13}\frac{erg}{scm^2}$
34	RY Tau	0.52	0.92	0.55
35	T Tau	0.87	0.81	1.4
79	SU Aur	0.30	0.39	0.28
80	RW Aur	0.85	3.2	0.95
85	GW Ori	0.80	0.57	0.53
251	RU Lup	1.7	4.0	1.5
271	AK Sco	1.4	2.8	1.6
315	DI Cep	0.64	0.71	0.37

The predicted intensity ratios Si III]/OIII] vs. Si III]/C III] are presented in Fig.3 for different values of V_0 and N_0. We have overplotted the location of the TTSs (filled triangles) on the diagram. Notice that most of the stars have lines flux ratios which are compatible with those predicted by the model: density of infalling gas log N_0 (cm^{-3}) $\sim$ 10.5 – 13 and shock speeds between 200 and 400 km s^{-1}.

The shock parameters V_0 and N_0 inferred from Fig. 3 can be used to derive from Fig. 1 the expected intensity I^n of the Si III]$_{1892}$ line. It is possible now to estimate surface area S_{ac} of the accretion zone from Eq.(1) and then the accretion rate, which is given by,

$$\dot{M}_{ac} = \mu_i m_H N_0 V_0 S_{ac} \qquad (3)$$

where $m_H = 1.67 \times 10^{-24}$ g is the mass of the Hydrogen atom and $\mu_i = 1.3$ is the mean molecular weight of the accreted matter. Normalizing for the typical values found in

the TTSs we find:

$$\dot{M}_{ac} = \left(3.4 \times 10^{-9}\frac{M_\odot}{yr}\right) N_{11} V_7 \frac{F_{-13}\, d_{100}^2}{I_5^n} \exp\left(0.92 A_\lambda\right) \qquad (4)$$

where N_{11} is given in units of 10^{11} cm^{-3}, V_7 in 10^7 cm s^{-1}, F_{-13} in 10^{-13} erg s^{-1}cm^2, I_5^n in 10^5 erg s^{-1} cm^{-2} ster^{-1} and d_{100} in hundreds of parsecs.

Notice that the reliability of the accretion rates determined from (4) depends strongly (exponentially) on the accuracy of the extinction derived for the star, unfortunately this is often ill determined. For instance Beckwith et al (1990) quote an $A_V = 2.7$ mag for RY Tau while Hartigan et al (1995) quote $A_V = 0.55$ mag. Therefore we shall derive the accretion rate just for a sample star to show up how this method can be used to derive accretion rates in the TTSs. We have selected for this purpose DI Cep.

DI Cep is a Classical TTS classified as G8 IV with a hot spot that emits in the UV (Gómez de Castro & Fernández 1996). The extinction for DI Cep is $A_V = 0.24$ mag (Yu et al 1986); this implies that assuming the extinction towards the star is well described by the standard ISM law then, $A_{\lambda 1892} = 0.62$ mag. As the distance to DI Cep is 300 pc (Kholopov 1959) we obtain that the accretion rate is: $\dot{M}_{ac}(DICep) = 1.9 \times 10^{-7} M_\odot yr^{-1}$, which is compatible with the constrains derived from the UV excess (Gómez de Castro & Fernández, 1996).

These data can also be used to calculate the surface of the emitting region (or the fraction of the stellar surface covered by infalling material) as well as the accretion luminosity ($L_{ac} = \dot{M}_{ac} V_0^2/2$).

5 CONCLUSIONS

We have shown from this analysis of the UV (IUE) data of the TTSs, that accretion shocks are consistent with the observed O III]$_{1665}$, Si III]$_{1892}$ and C III]$_{1909}$ lines *fluxes and their ratios*. In principle, the method allows to determine the velocity and the density of the accreting matter accurately in a manner which is independent of the current uncertainties in the distance and A_V measurements. This method is also well suited to derive other parameters as the surface of the accretion zone, the accretion rate and the accretion luminosity, however all these values are affected by the current uncertainties in the determination of the TTSs distances, extinctions and radii.

It was assumed that plasma moves along field lines of global stellar magnetic field, so global field has not any influence on the parameters of the shock. However generally speaking the semiforbidden lines ratios depend not only on V_0 and N_0, but also on the strenght of the chaotic magnetic field frozen into the accreted plasma as well as on the ion abundance far from the shock: the magnetic field will reduce the compression behind the shock while a large preionization fraction will tend to increase the fluxes emitted by the more ionized species. Given the low gas temperature and the low level of ionizing radiation (Martin, 1996), it is expected that the ion abundance far from the shock is small. At the same time our model is only applicable if the chaotic field strength H, is low enough to reduce appreciably the gas compression, but high enough to suppress electron heat
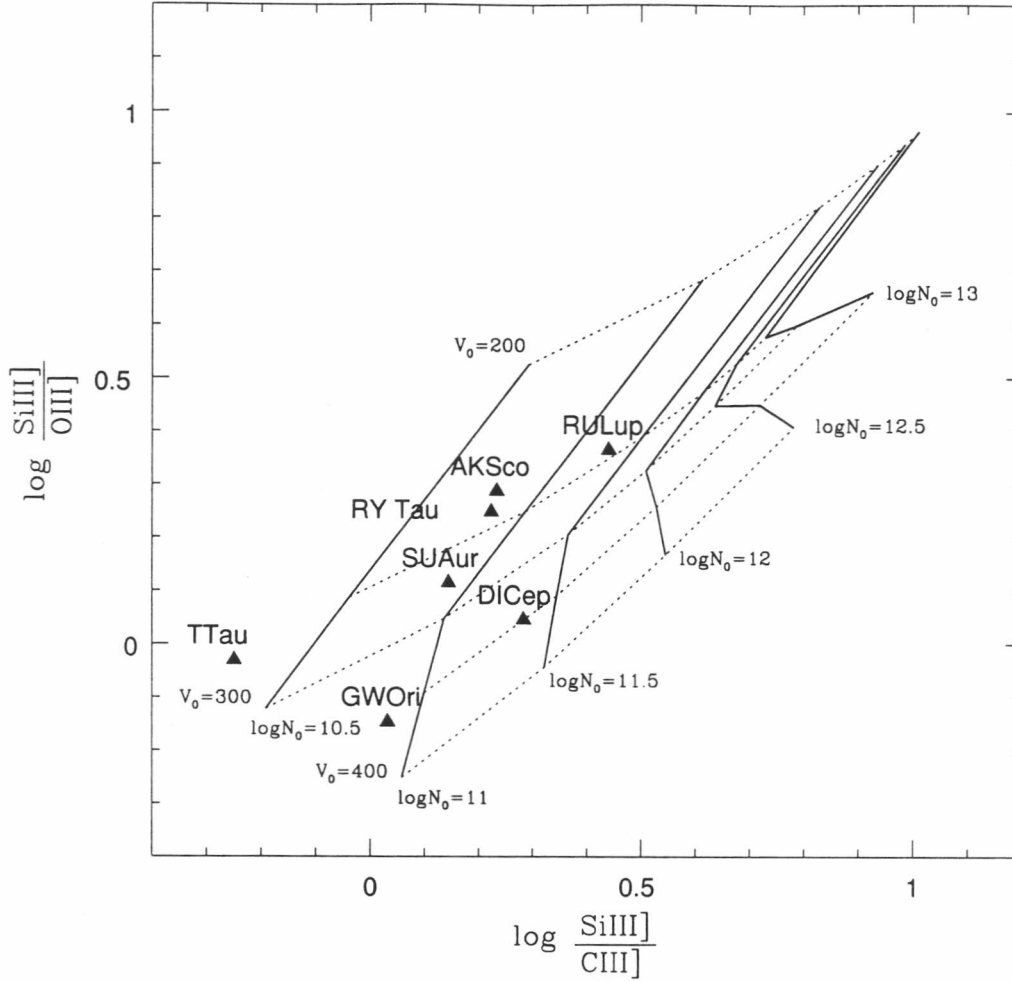
Figure 3. The Si III]/OIII]vs. Si III]/C III]intensity ratios as a function of the infall gas velocity V_0 for different values of the infall gas density N_0. Isodensity models are connected with continuous lines for $\log N_0 = 10.5, 11, 11.5, 12, 12.5$ and 13. Isovelocity models are connected with dashed lines for $V_0 = 200, 250, 300, 350$ and 400 km s^{-1}. The location of the TTSs of Table 1 is marked.

conductivity, e.g. $0.01\,G < H < 1\,G$ (see Lamzin (1998) for details).

Theoretical line ratio was calculated for ~ 20 additional UV semiforbidden lines in the paper Lamzin & Gomez de Castro, 1998. Unfortunately most of these lines are too weak to be detected with IUE satellite, but we hope they will be found in future HST spectra. Then one can use much more information to test the accretion model and estimate the accretion shock wave parameters more reliably.

We want to remark that for an homogenous accretion flux our results are independent of the geometry of the accretion zone. In other words, this shock diagnostic method does not depend on the precise geometry of the magnetic field since in our model the magnetic field is only used to the define the stream lines of the accretion flow. In fact, our theoretical predictions are also applicable to possible accretion shocks caused by mass transfer between close binaries. This may be indeed the case of AK Sco, which is a spectroscopic binary with orbital period P=13.^{d}6 and projected separation between the components of $a \sin i$=0.143 AU (Mathieu, 1994).

We want to emphasize that this method is best suited for the analysis of high spectral resolution data. High resolution spectroscopy will allow us to ascertain the line identification and to substract out the contribution of nearby strong lines to the total flux. Moreover, the possible contributions of the chromosphere and the wind (shocks) to the line flux can be sorted out in high resolution profiles by means of its kinematical signature.

As a final remark, let us note that high resolution profiles of the optically thin O III]$_{1665}$, Si III]$_{1892}$ and C III]$_{1909}$ lines can also be used to find out the geometry of the accretion zone by comparison between the theoretical and the observed profiles.

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ACKNOWLEDGEMENTS

REFERENCES

Beckwith, S.V.W., Sargent, A.I., Chini, R.S., Gusten, R., 1990, AJ, 99, 924

Gómez de Castro, A.I., Fernández, M., 1996, MNRAS, 283, 55

Gómez de Castro, A.I., Franqueira, M., 1997, *ULDA Access Guide to T Tauri Stars observed with IUE*, ESA SP-1205, Ed. ESA Publications Division, ESTEC, Noordwijk, The Neetherlands.

Gómez de Catsro, A.I., 1998, *Ultraviolet Astrophysics beyond the IUE Final Archive*, in press. Ed. ESA Publications Division, ESTEC, Noordwijk, The Neetherlands.

Hartigan, P., Edwards, S., Ghandour, L., 1995, ApJ, 452, 736

Hartmann L., Hewett R., and Calvet N., 1994, ApJ 426, 669

Huélamo et al, 1998; in preparation

Kholopov, P.N., 1959, SvA, 3, 291

Lamzin S.A., 1995, A&A, 295, L20

Lamzin S.A., 1998, Astronomy Reports, 42, 322

Lamzin S.A., Gomez de Castro A.I., 1998, Astronomy Lett., 24, 748 (English translation will apper in November issue of Astronomy Letters)

Martin S.C., 1996, ApJ 470, 537,

Mathieu, R.D., 1994, ARAA, 465

Muzerolle J., Calvet N., Hartmann L., 1998, ApJ, 492, 743

Yu K. et al., 1986, Astron. Tsirk, 1459, 5