ACCRETION IN YOUNG STARS: MEASURE OF THE STREAM VELOCITY OF TW HYA FROM THE X-RAY DOPPLER SHIFT

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CONTEXT

1. ACCRETION IN LOW MASS STARS

Young low-mass stars, during their initial evolutionary phases, accrete material from their circumstellar disk. These stars are defined as Classical T Tauri Stars (CTTS). The accretion process is regulated by the intense stellar magnetic fields, that disrupt the inner disk at a few stellar radii, and guide accreting material in a free fall toward the central star (Fig. 1). At the base of the stream, infalling material reaches velocities of ≈ 300 – 500 km s^{-1}, and a strong shock forms because of the impact with the denser stellar atmosphere (Königl 1991) .

2. X-RAYS FROM ACCRETION

High-resolution X-ray spectra of CTTS indicated that in these sources the plasma at a few MK is at high density (Kastner et al. 2002), at odds with other non-accreting low-mass stars (e.g. Testa et al. 2004), where X-rays are emitted by coronal plasma. This high density has been considered the main evidence that the cool plasma component in CTTS is not coronal plasma, but it is material heated in the accretion shock. In fact the infall pre-shock velocities, v_{pre}, are expected be so high to produce a post shock plasma at temperature of a few MK. The post shock plasma is also expected to move with a post shock velocity $v_{post} = v_{pre}/4$ (Fig. 1).

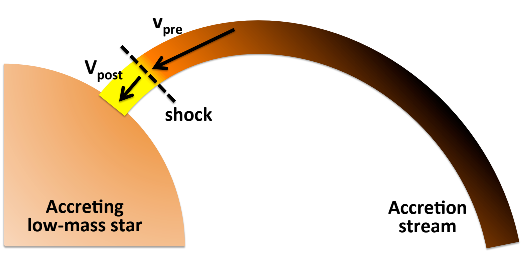

Figure 1. Schematic view of the accretion stream in a CTTS. The yellow area at the base of the stream indicates the hot plasma heated in the accretion shock and emitting X-rays.

3. THE CHANDRA AND XMM ERA

High-resolution X-ray spectra are proved to be a unique tool to investigate the accretion process in CTTS: soft X-rays directly probe the base of the acccretion stream, allowing to infer the physical conditions of the accreting material, like density and chemical composition. The effective area of the *Chandra* and *XMM* gratings allowed to gather high-resolution X-ray spectra only for a very few CTTS, leaving important issues to be addressed, like the mass accretion rate estimates (Curran et al. 2011), or the possibility to have an accretion feed corona (Brickhouse et al. 2010).

4. AIMS OF THIS WORK

Here we show for the first time the estimate of the radial velocity of the X-ray emitting plasma in CTTS by measuring the line Doppler shift in the X-ray band. A redshift with respect to the stellar photosphere, expected for the plasma located in the post-shock region (Fig. 1), would definitively indicate that this plasma is located in the accretion-shock region.

To this aim we analyzed the deep (500 ks) *Chandra*/HETGS observation of the CTTS TW Hya. TW Hya is a single 0.7 $M_\odot$ star, 8 Myr old, with an X-ray luminosity of 1.4×10^{30} erg s^{-1}, and with an accretion rate of ≈ 10^{-9} $M_\odot$ yr^{-1}. This star, located at 55 pc, is observed almost pole on.

DOPPLER SHIFT MEASUREMENTS WITH CHANDRA/HETGS

5. METHOD

To measure the Doppler shift in X-ray spectra gathered with *Chandra*/HETGS we have:

- selected a sample of strong and isolated emission lines (Table 1),
- fitted each line individually, adopting a gaussian profile, to determine the centroid position (two examples are reported in Fig. 2),
- determined the velocity corresponding to the displacement of each line with respect to its rest wavelength,
- computed the weighted mean of these velocities (indicated with v_X),
- evaluated the Earth velocity toward the target (indicated with v_E),
- compared v_X+v_E (i.e. the X-ray plasma radial velocity with respect to the barycentric reference system) with the predicted radial velocity of the star (indicated with v_0).

6. REFERENCE STAR SELECTION

To test the reliability of our method we have applied it also to low-mass stars that:

- have been observed with *Chandra*/HETGS providing spectra with high signal to noise ratio,
- are not affected by orbital motion with high radial velocities,
- have X-ray emission due only to coronal plasma, since coronal plasma is not expected to have bulk motions with respect to the stellar photosphere.

All the stars, and the corresponding *Chandra*/HETGS spectra analyzed, are listed in Table 2.

7. RESULTS

The radial velocities measured from the X-ray spectra (v_X) and their comparison with the expected photospheric velocities are reported in Table 2, and plotted in Fig. 3. From these values we find that:

- the X-ray emitting plasma on TW Hya shows a significant redshift with respect to the stellar surface, corresponding to a velocity of 36.5 ± 4.7 km s^{-1};
- all the other stars show X-ray emitting plasma velocities compatible with that of the stellar photosphere, validating the adopted method.

Figure 4 reports, as an example, the comparison of the O VIII line profiles of all the targets.

Table 1. Line selected for the Doppler shift measurements.

wavelength (Å)	Ion	T_{max} (MK)
10.24	Ne X	6
13.70	Ne IX	4
16.01	O VIII	3
18.97	O VIII	3
21.60	O VII	2

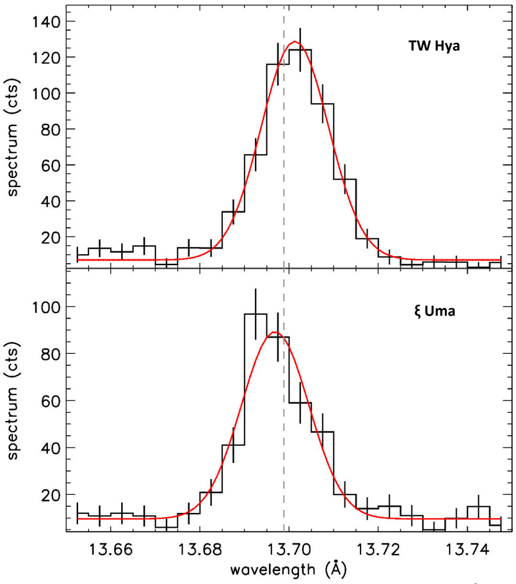

Figure 2. Observed spectra (black line) in the region of Ne IX line at 13.70 Å. Red curve indicates the best fit of the line. The two spectra, TW Hya in the upper panel and ξ Uma in the lower panel, represent the case of a red shifted and blue shifted line, respectively. The v_X corresponding to these spectra are reported in Table 2.

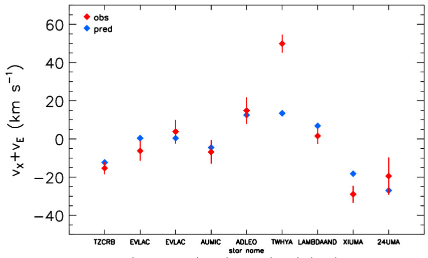

Figure 3. Comparison between the observed radial velocity in X-rays, $v_X + v_E$, (velocity with respect to the barycentric reference system, red diamonds), and the radial photospheric velocity (blue diamonds) for each inspected star.

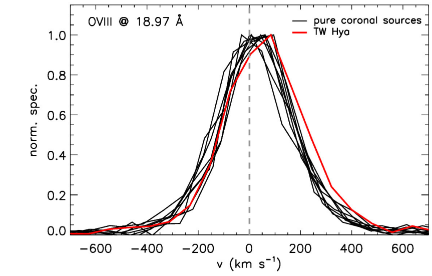

Figure 4. Observed profiles of the O VIII Lyα line, of all the X-ray spectra analyzed, with respect to the stellar reference frame. All the inspected stars, but TW Hya, show no shift with respect to the stellar frame. The redshift of the TW Hya X-ray spectrum is small but significant.

Table 2. Velocities measured from the X-ray emission lines, and velocities expected.

Star	*Chandra* Obs Id	v_X (km s^{-1})	v_E (km s^{-1})	v_0 (km s^{-1})	$(v_X+v_E)-v_0$ (km s^{-1})	$n\,\sigma$
TZ Crb	15	−5.0 ± 3.2	−10.3	−12.3	−3.0 ± 3.2	0.9
EV Lac (1)	1885	−9.0 ± 5.0	2.7	0.4	−6.7 ± 5.0	1.3
EV Lac (2)	10679	8.7 ± 6.2	−4.8	0.4	3.4 ± 6.2	0.5
AU Mic	17	21.3 ± 6.0	−28.2	−4.5	−2.4 ± 6.0	0.4
AD Leo	2570	43.4 ± 6.9	−28.5	12.5	2.4 ± 6.9	0.3
TW Hya	7435+7436+7437+7438	38.3 ± 4.7	11.6	13.4	36.5 ± 4.7	7.8
λ And	609	21.7 ± 4.2	−20.2	6.8	−5.3 ± 4.2	1.3
ξ UMa	1894	−52.7 ± 4.4	23.7	−18.2	−10.8 ± 4.4	2.4
24 UMa	2564+3471	−1.9 ± 9.7	−17.6	−27.0	7.5 ± 9.7	0.8

CONCLUSIONS AND FUTURE PERSPECTIVES WITH ATHENA

8. THE ACCRETION ONTO TW HYA

We have measured for the first time the radial velocity of the X-ray emitting plasma in a CTTS. In particular we have found that the plasma at a few MK on TW Hya is redshifted of 36.5 ± 4.7 km s^{-1} with respect to the stellar photosphere. We can deduce that:

- soft X-rays in CTTS are indeed produced in the post shock region;
- for TW Hya X-ray and UV lines (in particular the narrow component of the C IV line, Ardila et al. 2013) provide very similar radial velocities, indicating that the plasma components at 10^6 K and that at 10^5 K are located in the same structure, i.e. the post-shock region at the base of the accretion stream;
- the post-shock plasma is expected to have a velocity v_{post} of ≈ 100 km s^{-1} (a minimum value of v_{pre} is needed to have a post shock hot enough to radiate in X-rays, Sacco et al. 2010); then, since TW Hya is observed from the pole, an observed radial velocity for the post shock of ≈ 35 km s^{-1} indicates that the base of the accretion stream is located at low latitudes on the stellar surface.

9. ACCRETION IN YOUNG STARS WITH ATHENA

The extremely larger effective area of *ATHENA*/X-IFU, with respect to the *Chandra* and *XMM* gratings, together with a spectral resolution of 1.5 eV in the soft X-ray band, will allow to:

- enormously increase the number of CTTS for which high resolution X-ray spectra can be gathered; up to now only a few CTTS have been investigated with high resolution X-ray spectroscopy, with *ATHENA* it will be possible to investigate accreting stars at different ages, different accretion rates, different accretion geometries;
- investigate accretion on very short time scales, i.e. down to 1 ks; up to now CTTS X-ray spectra are integrated over exposures of ≈100 ks, while instead monitoring in other wavelength bands have proved that accretion varies on significantly shorter time scales.

One of the goals for the X-IFU instrument is the measurement of bulk velocities, reaching ≈20 km s^{-1} as the minimum error from each individual spectral line. This resolution will allow to:

- measure the radial velocity of the post-shock plasma for several CTTS, exploring intrinsic and rotationally modulated variations of v_{rad}. Up to now TW Hya is the only CTTS for which the radial velocity measurements in X-rays is possible.

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