Simultaneous X-ray and Optical Observations of the T Tauri star TW Hya

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Summary. We report preliminary results obtained from a spectroscopy and photometry campaign of the T Tauri star TW Hya in February- March, 2007. A long HETG observation with CHANDRA and simultaneous optical observations around the world have been carried out to investigate the relationship between the X-ray emission and optical variability and to connect these to the accretion and wind characteristics of the star.

Keywords. T Tauri stars, X-ray emission, accretion, optical variability

1 Introduction

TW Hya is unique in many ways. It is ∼10 Myr old, one of the oldest T Tauri stars still accreting material from its circumstellar disk onto the star via accretion streams that are believed to be magnetically funnelled. It is nearby at a distance $\sim$ 50pc and isolated from the sites of star formation, and therefore has minimal obscuration effects. The $H\alpha$ emission line is unusually broad with FWHM often as large as 200-400 km^{-1} and has a distinct weakening of the short wavelength side of the profile (a 'blue asymmetry') implying the presence of a stellar wind/mass outflow. TW Hya is also one of the brightest T Tauri stars in X-rays. An HST image has confirmed that it is oriented pole-on (Krist et al. 2000), with the circumstellar (CS) disk almost face-on in the sky having a small inclination angle of $\sim 6^o$ (Qi et al. 2006), and as a result reddening effects are negligible. The accretion and wind characteristics of the star therefore can be studied without confusion from its CS disk. Because of these attributes, the star continues to intrigue astronomers for it offers a unique opportunity to study the important process of stellar accretion.

TW Hya shows a rich but confusing pattern of photometric variability. The rotation period has been reported at different epochs in the past to range from 1.28 (Herbst & Koret 1988) to 2.8 days (Lawson & Crause 2005) to even longer periods determined from recent observations. A detailed analysis based on observations over several years by Mekkaden (1998) yielded a period of

2.196d for the light variation. With spot modelling, this variation was ascribed to a hot spot with T = 8450K, almost situated at the pole and covering a small fractional surface area. In addition to this periodic light variation, sudden brightenings lasting a day or two were noticed which could be due to short-lived hot spots produced by a varying accretion rate. These seem to be a regular feature of TW Hya. Since the brightenings could occur at any photometric phase, they could completely mask the periodic variation and thus hide the true period of the star.

The other controversy relates to the relative roles that accretion and coronal emission play in contributing to the source of its X-ray emission. It is possible that X-ray emission from accretion on to T Tauri stars may be diminished because the hot shock from the accreting material might form too deep in the photosphere for the X-rays to escape. Also, accretion-dominated X-ray production challenges the long-standing view that X-rays from T Tauri stars originate in coronal magnetic loops which is supported by many CHANDRA observations of star forming regions (Gagné et al. 2004; Preibisch et al. 2005). However, Kastner et al. (2002) argue for an accretion origin of X-rays based on the O VII and Ne IX forbidden (*f*) to intercombination (*i*) line ratios from the X-ray spectrum of TW Hya obtained from a single 48s HETG/CHANDRA observation. These yield densities $N_e \sim 10^{13} cm^{-3}$, much higher than found in coronal sources where they lie between $2 \times 10^{10} - 10^{12} cm^{-3}$.

2 World wide campaign of observations

In order to resolve this controversy, CHANDRA devoted a major Guest Observer program (N.S. Brickhouse, PI) to a long (500 ks) HETG observation of TW Hya to obtain a high quality spectrum during 15 February - 3 March, 2007 with short gaps in between (15-17 Feb : 160ks; 26 Feb-3 Mar : 160+160+20ks). Simultaneous optical observations were carried out at several observatories around the world to provide almost continuous coverage to relate the accretion properties and variability of TW Hya to its X-ray emission. These are listed below :

1. MIKE echelle spectra from the 6.5m Magellan/Clay telescope, Chile (A.K. Dupree)
2. Echelle spectra from the 2.3m telescope at Mt. Stromlo, Australia (M.S. Bessell & W.A. Lawson)
3. SARG echelle spectra from the TNG at La Palma (DDT time & R. Pallavicini)
4. Coude spectra from the 1.6m telescope at Pico do Dias, Brazil (J. Luna)
5. Echelle spectra from the 2.3m telescope at VBO, India (S.V. Mallik)
6. Photometry & spectroscopy at SAAO, South Africa (W.A. Lawson & L.A. Crause)
7. IR spectra with Phoenix on Gemini-S (S. Schuster)

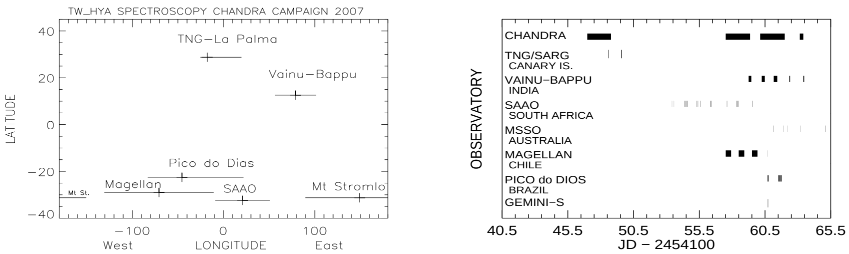

Fig. 1. The world wide campaign. ***Left panel:*** **Location of the observatories in longitude.** ***Right panel:*** **Observations acquired during the campaign.**

It is evident from Fig.1 (*left panel*) that the Vainu Bappu Observatory (VBO) at Kavalur, India fits in the gap, being at just the right longitude to complete the coverage. At RA = $11^h01^m52^s$, TW Hya is observable practically all night during Feb./Mar. Several spectra were obtained each night from Feb.27 to Mar.3 with the echelle spectrograph on the 2.3m telescope at VBO at a resolution of 28000. Fig.1 (*right panel*) shows that the coverage by various observatories around the world occur in conjunction with the CHANDRA measurements.

3 X-ray emission observations

Fig.2 (*top panel*) displays the X-ray light curve measured with CHANDRA. Excluding the flare that occurred over 20ks of the 500ks observation, the total X-ray flux from TW Hya varied by a factor of 2; it did not show any periodic variations during the CHANDRA sequence that spanned 16.5 days. This is in contrast to the periodic variability observed in the optical spectra obtained at the same time. Line-based light curves from the low temperature (2.4 MK) gas associated with the shock show less variability than light curves from the hot (10 MK) coronal gas. The flare appears to be coronal in nature. It may be difficult to separate the variability of the accretion emission from that of the corona in order to compare to optical photometry.

4 The behaviour of $H\alpha$ line profiles

The optical observations were strikingly different. Here we will highlight the $H\alpha$ spectra from VBO and Magellan. A detailed report of all optical observations is given elsewhere (Dupree et al. 2009). Fig.3a shows the spectra from VBO superposed over one another for the nights Feb27-Mar3. For each night, it is averaged over all the profiles for that night except for Mar.2. Profiles of the first 2 nights (27, 28 Feb. 2007) are highly anomalous and the variation

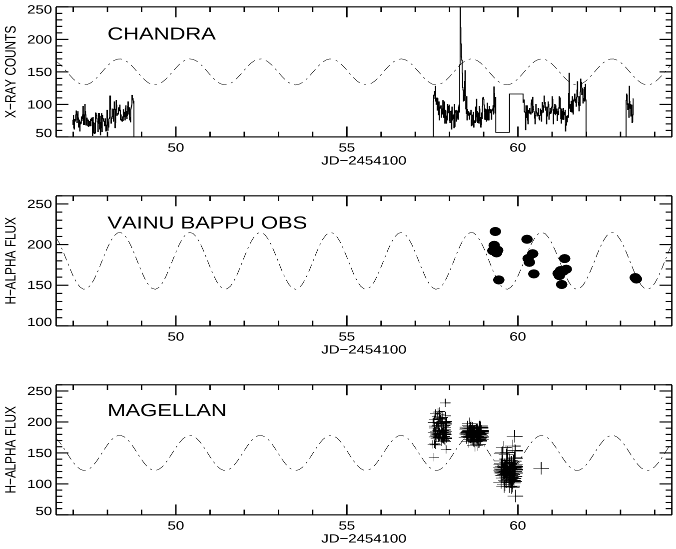

Fig. 2. Total X-ray CHANDRA counts binned in 1000s intervals vs. time (*top panel*); $H\alpha$ **fluxes from the Vainu Bappu Observatory measures** (*centre panel*), **and the MIKE echelle spectrograph on the Magellan/Clay telescope at Las Campanas, Chile** (*lower panel*). **A sine curve (period 2.06d) is overlaid on each data set**

in the profile shape and strength in subsequent nights is remarkable. There is unusual enhanced emission on the negative velocity ('blue' side) of the profile allowing the broad accretion profile to assume a natural symmetric shape; later the blue emission became weaker and the asymmetry was re-established on subsequent nights, the profile then assuming its typical shape. The Magellan/MIKE spectra with much better S/N ratio obtained by Dupree et al. (2009) during Feb.26-Mar 1 showed a similar pattern in line profile shapes. A 20ks X-ray flare occurred between night 1 and 2 of the MIKE observations as seen in Fig.2. The spectrum of night 1 already looked anomalous and therefore may not be related to the occurrence of the flare. Flares occur quite frequently in stars like TW Hya but the $H\alpha$ profiles observed in 2007 are very different from the numerous profiles of TW Hya in the literature. For comparison, those observed in 2004 by Dupree et al. (2007) are reproduced here in Fig.3b. These revealed periodic systematic variations in the flux, velocity and the shape of the profile. Absorption features occurred at high outflow velocities between $-100ks^{-1}$ and $-300ks^{-1}$. They were stable in velocity and recurred similarly in 2006. The fact that there are variations suggests accretion is not uniformly distributed over the stellar hemisphere in view and is consistent with the photometric variations found by Lawson & Crause (2005) and Mekkaden (1998). But the repetition of absorption notches at the same velocities implies stable atmospheric structures, possibly controlled by the stellar magnetic field configuration that channels the accreting material from the disk to the star.

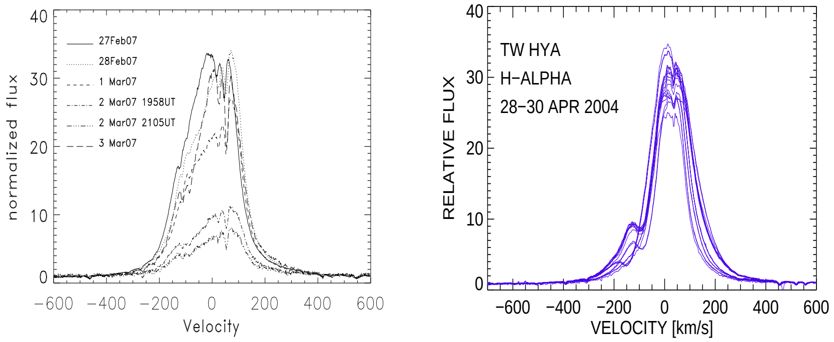

Fig. 3. a) 2007 spectra of $H\alpha$ from VBO. b) 2004 $H\alpha$ spectra at Magellan

However, the $H\alpha$ profiles of 2007 are not like any seen in the past, to our knowledge. The largest difference appears as an enhancement of emission on the short wavelength side. This anomalous phenomenon is unlikely to arise from enhanced accretion because the long wavelength side of the profile should show a similar large enhancement. We note that the observed X-ray emission does not change during this period. It may be that this apparent excess blue emission reflects a changing wind opacity. Although optical profiles from T Tauri stars are usually modelled as arising from accretion (Muzerolle et al. 2000), our observations imply that wind opacity has a substantial role in modifying the profiles. The stellar wind appears to be suppressed. The observed profile changes may result from a changing viewing orientation of the accreting column and/or wind as the star rotates, causing more or less opacity or from a fundamental change in the magnetic field configuration or both. It is clear that TW Hya is in an active phase of accretion and/or wind and that the accretion/wind pattern did indeed change between 2004 and 2007. Much more is to be extracted from the spectra observed and the analysis is in progress. A summary of the optical observations will be given elsewhere (Dupree et al. 2009). Work is also in progress to derive temperatures and densities from a variety of diagnostics contained in the CHANDRA data (Brickhouse et al. 2009).

5 Mystery of the rotation period

Fig.2 shows a sine curve placed through the X-ray light curve and the $H\alpha$ fluxes obtained at the VBO and Magellan. The period of 2.057d was derived from the SAAO $H\alpha$ coverage over the 7 day interval during the gap in CHANDRA measures. This is close to what Mekkaden (1998) obtained but differs from other periods that have been measured. Does the period change? Or does it appear to change? The picture of TW Hya variability is a complex one, particularly in view of recent radial velocity variation measurements of TW Hya by Setiawan et al. (2008) revealing a clear spectroscopic sinusoidal signal with a period of 3.56d which they interpreted as an indication of a 10 M_{Jup} planet orbiting around it. However, this claim has not held up. Huelamo et al. (2008) question the possibility and propose that Setiawan et al.'s observations could be reproduced by photospheric spot-induced spectral line shifts. Their own spectroscopic and photometric data are suggestive of the presence of short-lived hot spots that appear and disappear, hiding the true period of the star. Through sheer coincidence, the MOST satellite observed TW Hya (Rucinski et al. 2008) exactly during the time when RV observations of Setiawan et al. were collected. The MOST run lasted 11 days and indeed led to a detection of a well-defined photometric period of 3.7d. Because of the significance of this result and because the 2007 run was too short, it observed TW Hya in 2008 again for 47 days continuously. The picture of the 2008 run was very different. The strong 3.7d periodicity was entirely absent. According to Rucinski et al. (2008), it does not seem related to a possible planet because it disappeared within one year. Instead, a number of periodic components appear to be present at 7.7, 5.1, 3.3, 2.5, 1.7, 1.25d. This so called flicker noise variability spectrum may be a manifestation of hot spots, short-lived structures anchored in different parts of the accretion disk and thus masking the true rotation period. So the big question of the rotation period of TW Hya remains!

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