Mem. S.A.It. Vol. 88, 818

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HST & Chandra observations of the RY Tau jet

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Abstract. We summarize observations of the accreting T Tauri star (TTS) RY Tau with *HST* and *Chandra*. RY Tau drives a bipolar jet that has been extensively studied in the optical. A sensitive observation of RY Tau with *Chandra* in 2009 revealed faint X-rays extending outward to a separation of $\approx 1''.7$ arcsecs from the star, overlapping the bluehifted jet (P.A. $\approx$ 295°). The extended X-ray emission arises in plasma heated to at least T $\sim$ few MK by an as yet unidentified mechanism that is likely associated with the jet. To probe the inner jet at higher spatial resolution, we obtained *HST* STIS UV grating observations in 2014 with the STIS long-slit aligned along the optical jet. Spatially-resolved medium-resolution STIS G140M grating spectra show extended emission in the C IV doublet (1548/1551 Å) out to at least $1''$ along the forward (blueshifted) jet and out to $\approx 0''.5$ along the redshifted counterjet. The extended C IV emission traces warm plasma (T $\sim 10^5$ K) in the innermost jet and its presence will constrain jet-heating models.

Key words. stars: pre-main sequence – stars: jets – stars: individual (RY Tau)

1. Introduction

Chandra: A 55 ks ACIS-S X-ray observation in 2009 provided high-quality CCD images, spectra, and light curves (Skinner et al. 2011). Higher-resolution grating spectra (ACIS-S/HETG) were acquired in 2014 (Skinner et al. 2016). RY Tau is a luminous highly-variable X-ray source (log L_x = 30.5 - 31.2 ergs s^{-1} at d = 134 pc). Short-term ($\sim$hours) flare-like variability is present in addition to a slower modulation ($\sim$days) that may be linked to the star's rapid rotation. The characteristic X-ray temperature of the star is $T_x \sim$ 50 MK but can increase to $T_x \sim$ 100 MK during flares. The strong variability and high X-ray temperatures are indicative of intense magnetic activity. Fluorescent Fe emission at 6.4 keV is present, originating in cold material near the star irradiated by hard stellar X-rays. Deconvolved ACIS-S images in the 0.2 - 2 keV band (Fig. 1) reveal faint X-ray emission extending outward along the blueshifted optical jet, at least some of which is likely associated with the jet.

HST: STIS/MAMA UV grating observations were obtained in Dec. 2014 with the $52''$ $\times$ $0''.2$ slit aligned along the jet. We focus here on medium-resolution (0.075 Å FWHM) G140M spectra which spectrally resolve the C IV doublet. STIS spatial resolution is $\approx 0''.1$. STIS/MAMA 2D spectral images provide spatially-resolved spectra along the jet.

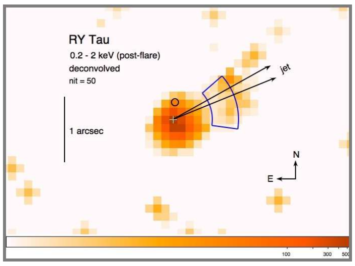

Fig. 1. Deconvolved *Chandra* ACIS-S image of RY Tau (Skinner et al. 2011). Some of the structure inside the sectored area may be PSF-induced.

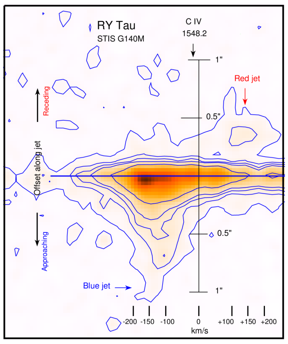

Fig. 2. Smoothed STIS G140M 2D spectral image of the RY Tau C IV 1548.2 Å line (Skinner et al., in prep.) Contours are at levels (2,4,6,8,16)e-13 ergs cm^{-2} s^{-1} Å^{-1} arcsec^{-2}. Velocity ticks are relative to the star's rest frame (RV = +18 km s^{-1}; Petrov et al. (1999).

2. HST view of the inner jet

The STIS data clearly show warm plasma (T ~ 10^5 K) traced by C IV out to ≈1″ along the blueshifted jet and to ≈0″.5 along the fainter redshifted jet (Fig. 2; Skinner et al. in prep.). The C IV 1548.2 Å line in a 1D spectrum extracted along the stellar trace with a spatial binning of 5 MAMA pixels (0″.145) is broad and asymmetric suggesting multiple contributions (e.g. star, unresoved inner jet, and possible H_2 1547.3 Å). The C IV 1550.7 Å line in the stellar trace spectrum is more symmetric and is roughly approximated by a Gaussian with FWHM ≈ 330 km s^{-1}. The C IV doublet lines become more symmetric and narrower moving outward away from the star along the jet. Spectra extracted at offsets of 0″.50 ± 0.″07 (67 ± 9 AU at 134 pc) in the blue jet are nearly Gaussian with a centroid shift of −130 ± 8 km s^{-1} relative to the stellar systemic velocity and line width FWHM = 136 ± 10 km s^{-1}.

3. Jet heating

What heats the jet to UV and X-ray emitting temperatures? The maximum predicted shock temperature is $T_s = 0.15[v_s/100 \text{ km s}^{-1}]^2$ MK where $v_s \leq v_{jet}$ is the shock speed. For an estimate we use a radial jet velocity $v_{rad} = -130$ km s^{-1} at a offset of 0″.5 in the approaching jet, as noted above. The deprojected jet speed v_{jet} depends on the jet inclination relative to the line-of-sight which is not well-constrained but previous work suggests i_{jet} = 61° ± 16° (Agra-Amboage et al. 2009). This gives v_{jet} = 268 [184 - 578] km s^{-1}. These values are high enough to account for the UV plasma (T ~ 0.5 MK) but cannot explain the hotter X-ray plasma unless v_{jet} is near the high-end of the allowed range and $v_s \approx v_{jet}$. Such high shock speeds comparable to the jet speed are questionable (Agra-Amboage et al. 2009). Thus, other heating mechanisms besides shocks may be involved. Magnetic heating (Ohmic dissipation) has been considered as a possible heating mechanism for the DG Tau jet (Schneider et al. 2013). But jet B-fields are weak (μG - mG; Carrasco-González et al. 2010) and probably non-uniform. More reliable B-field measurements are needed to test magnetic heating models. Hot plasmoids (T ~ 10 - 100 MK) ejected during magnetic-reconnection flares (Hayashi et al. 1996) could also produce faint extended X-rays. But if not reheated the plasmoids quickly cool below X-ray temperatures and any extended X-ray structure would be ephemeral.

Acknowledgements. S.S. acknowledges support from grants SAO GO4-15012X and HST-GO 13714.

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