Resolving the Inner Arcsecond of the RY Tau Jet with HST

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Abstract

Faint X-ray emission from hot plasma ($T_x > 10^6$ K) has been detected extending outward a few arcseconds along the optically delineated jets of some classical T Tauri stars including RY Tau. The mechanism and location where the jets are heated to X-ray temperatures are unknown. We present high spatial resolution Hubble Space Telescope (HST) far-ultraviolet long-slit observations of RY Tau with the slit aligned along the jet. The primary objective was to search for C IV emission from warm plasma at $T_{C\ IV} \sim 10^5$ K within the inner jet ($<1\arcsec$) that cannot be fully resolved by X-ray telescopes. Spatially resolved C IV emission is detected in the blueshifted jet extending outward from the star to 1″ and in the redshifted jet out to 0″5. C IV line centroid shifts give a radial velocity in the blueshifted jet of $-136 \pm 10$ km s$^{-1}$ at an offset of 0″29 (39 au) and deceleration outward is detected. The deprojected jet speed is subject to uncertainties in the jet inclination, but values $\gtrsim 200$ km s$^{-1}$ are likely. The mass-loss rate in the blueshifted jet is at least $M_{\text{jet\,blue}} = 2.3 \times 10^{-9}$ $M_\odot$ yr$^{-1}$, consistent with optical determinations. We use the HST data along with optically determined jet morphology to place meaningful constraints on candidate jet-heating models including a hot-launch model in which the jet is heated near the base to X-ray temperatures by an unspecified (but probably magnetic) process, and downstream heating from shocks or a putative jet magnetic field.

Key words: ISM: jets and outflows – stars: individual (RY Tau) – stars: mass-loss – stars: pre-main sequence – ultraviolet: stars

1. Introduction

Highly collimated outflows, or “jets,” are a widespread phenomenon in astrophysics and have been detected in a diverse range of objects including young stars and protostars, compact binaries, planetary nebulae, and active galactic nuclei (AGNs) (reviewed by Livio 1999). In star-forming regions, jets are usually associated with accreting protostars, classical T Tauri stars (cTTS), and Herbig Ae/Be stars and are revealed in the optical as shock-excited Herbig–Haro (HH) objects. As such, jets provide an excellent laboratory for studying shock physics. Jets from young stars inject turbulence into the surrounding molecular cloud. Jet rotation, along with other mechanisms, may remove angular momentum from the accretion disk (reviewed by Frank et al. 2014). Possible detections of jet rotation in a few young stellar objects have been reported, a recent example being the protostellar system HH 212 (Lee et al. 2017). However, searches for jet rotation signatures in RY Tau, the cTTS of primary interest here, have so far not yielded a high-confidence (>3σ) detection ( Coffey et al. 2015).

Jets from young stars have traditionally been identified and studied using optical and radio telescopes, both of which can provide sub-arcsecond resolution. Optical studies of forbidden spectral lines yield information on properties of cool ($T \sim 10^4$ K) plasma in shocked jets. Somewhat surprisingly, much hotter X-ray plasma at temperatures $T_x \gtrsim 10^6$ K has now been detected at small offsets ($\lesssim 4″$) along the jets of some young stars such as DG Tau (Güdel et al. 2005, 2008), Z CMa (Stelzer et al. 2009), RY Tau (Skinner et al. 2011), and possibly RW Aur A (Skinner & Güdel 2014). Faint extended jet emission has also been reported in the vicinity of a few jet-driving protostars such as L1551 IRS 5 (Bally et al. 2003; Schneider et al. 2011) and Herbig–Haro objects (Pravdo et al. 2001; Favata et al. 2002; Grosso et al. 2006; Pravdo et al. 2004).

The mechanism(s) by which jets from young stars are launched, collimated, and heated are not fully understood, but it is thought that magnetic fields play a key role. Shocks undoubtedly also play a role in jet heating, but it is not yet clear that shocks alone can heat jets from young stars to X-ray emitting temperatures. To reach X-ray temperatures of a few MK, jet speeds (and shock speeds) of at least $v_j \approx 300$–400 km s$^{-1}$ are required. However, some jet-driving TTS for which faint extended X-ray jet emission has been detected apparently do not achieve such high jet speeds, and other heating mechanisms besides shocks may be at work.

Of specific interest here is RY Tau, a relatively massive cTTS, whose properties are summarized in Table 1. It is remarkable in several respects, being a rapid rotator with $v\sin i = 52 \pm 2$ km s$^{-1}$ (Petrov et al. 1999) and a bright variable X-ray source indicative of strong magnetic activity (Skinner et al. 2016). It is undergoing disk accretion (Schegerer et al. 2008; Agra-Amboage et al. 2009), and mass loss is present from a wind (Kuhi 1964; Gómez de Castro & Verdugo 2007) and a bipolar jet known as HH 938 (St.-Onge & Bastien 2008). Searches for a companion have so far yielded negative results (Leinert et al. 1993; Schegerer et al. 2008; Pott et al. 2010).

Continuum-subtracted Hα images obtained by St.-Onge & Bastien (2008) traced the approaching (blueshifted) jet outward to 31″ from the star along P.A. $\approx 295°$ and inward to within 1″5 of the star. These images also show more distant features attributed to the receding counterjet at offsets of $\approx 2′′3–3′′5$ from the star. A sub-arcsecond resolution ground-based study of the jet using the Canada–France–Hawaii Telescope by Agra-Amboage et al. (2009) revealed high-velocity ($\gtrsim 100$ km s$^{-1}$)
jet plasma extending outward to at least $1''$ from the star. After taking into account projection effects due to the jet inclination angle to the line of sight ($\theta_{\text{jet}} = 61^\circ \pm 16^\circ$), they estimated the most probable deprojected jet speed to be $v_{\text{jet}} \approx 165 \text{ km s}^{-1}$. This value is too low to explain the faint extended X-ray emission seen in deconvolved Chandra images overlapping the blueshifted jet in terms of a jet that is heated only by shocks (Skinner et al. 2011).

The above results raise the question of whether hotter and higher speed jet plasma could have escaped detection in ground-based optical studies. We investigate this possibility here by acquiring spatially resolved far-ultraviolet (FUV) spectroscopic images of the inner jet using the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS). As discussed in more detail below, the new STIS spectra show that the jet speed is higher than measured in optical studies, but is still only marginally sufficient at best to produce shock-induced X-rays.

### 2. Observations and Data Reduction

The HST STIS long-slit observations of RY Tau were obtained in 2014 using the Multi-Anode Micro-channel Array (MAMA) detectors. In contrast to previous STIS observations (Calvet et al. 2004), the $52'' \times 0''/2$ slit was aligned along the optical jet axis to sample emission along the jet. Table 2 summarizes the observations and basic instrument properties.

We focus here on the medium-resolution G140M spectrum, which spectrally resolves the CIV resonance doublet whose reference wavelengths are listed in the CHIANTI atomic database (Del Zanna et al. 2015) as $\lambda_{\text{ref}} = 1548.189/1550.775 \text{ Å}$.

The G140M grating provides detailed information on line centroid wavelengths (velocities) and shapes with a FWHM spectral resolution of $\approx 0.075 \text{ Å}$, equivalent to $\approx 15 \text{ km s}^{-1}$ at 1550 Å. The CIV doublet traces warm plasma at a characteristic temperature $T_{\text{CIV}} \sim 10^5 \text{ K}$ and has been brightly detected in previous HST observations of RY Tau (Calvet et al. 2004; Ardila et al. 2013).

Data were analyzed using PyRaf v. 2.1.6. Flat-fielded calibrated 2D image science files ("flt.fits") for each exposure were provided by the Space Telescope Science Institute (STScI) production pipeline. The flat-fielded images for exposures taken at dithered offset positions were shifted and aligned with images for undithered exposures. The set of aligned flat-fielded images was then combined into a total exposure 2D spectral image (Figure 1) using the Pyraf task x2d. Calibrated and background-subtracted 1D spectra giving flux density as a function of wavelength were extracted from flat-fielded calibrated images using the task x1d. Wavelengths in the 2D spectral image and 1D spectra are in the heliocentric reference frame. We extracted spectra centered on the stellar trace for individual exposures (typical exposure time 815 s) to check for time-variable CIV emission and for the total usable summed exposure of 10,765 s. In addition, 1D spectra based on the total exposure were extracted at incremental offsets $0''/145$ (five MAMA pixels) along the blueshifted and redshifted jets.

The spectra at each offset were extracted using a spatial binsize of five MAMA pixels (full width). This strategy provides complete non-overlapping spatial sampling along the jet. The choice of a five-pixel step size and a five-pixel spatial binsize for each spectral extraction is a compromise between the need to obtain good spatial sampling while capturing sufficient counts in each spectrum to reliably measure line parameters. Taken together, the 1D spectra provide spatially resolved information on the jet radial velocity, line width, and flux as a function of projected distance from the star. Decreasing signal-to-noise ratio (S/N) in the CIV lines toward larger offsets.

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**Table 1**

| Sp. Type | $M_*$ ($M_\odot$) | $V$ (mag) | $A_V$ (mag) | $l_{\text{jet}}$ ($L_\odot$) | log $L_*$ (erg s$^{-1}$) | $v_{\text{rad}}$ (km s$^{-1}$) | log $M_{\text{bol}}$ ($M_\odot$, yr$^{-1}$) | $d$ (pc) |
|----------|----------------|-----------|-------------|----------------|-----------------|-------------------|---------------------|---------|
| F8 III—G1-2 IV | 1.7–2.0 | 9.3–11 (v) | 2.2 ± 0.2 | 15.3 | 30.5–31.2 | 18 ± 1 | −7.3 ± 0.3 | 134 |

**Note.** Data are from Agra-Amboage et al. (2009), Calvet et al. (2004), Kenyon & Hartmann (1995), Petrov et al. (1999), and Schegerer et al. (2008). Spectral type is uncertain (Holtzman et al. 1986). The visual extinction ($A_V$) is from Calvet et al. (2004) but smaller values have been used in other studies (see text). The bolometric luminosity is based on $L_{\text{bol}} = 16.7 L_\odot$. ($d = 140$ pc) from Kenyon & Hartmann (1995), and has been normalized to $d = 134$ pc. The X-ray luminosity $L_x$, is from Skinner et al. (2016) and is variable. The heliocentric radial velocity ($v_{\text{rad}}$) is from Petrov et al. (1999) and is consistent with an earlier measurement $v_{\text{rad}} = 16.5 \pm 2.4$ km s$^{-1}$ obtained by Hartmann et al. (1986). Distance is from Bertout et al. (1999).

**Table 2**

| Start (UT) | Stop (UT) | $\lambda$ ($\text{Å}$) | Resolution FWHM ($\text{Å}$) | Plate Scale ("/pixel) | Dispersion ($\text{Å}$/pixel) | Exposures | Time (s) |
|------------|-----------|----------------|-----------------------------|-----------------|-----------------------------|-----------|---------|
| 2014-12-04 23:53 | 2014-12-05 07:39 | 1522–1578$^a$ | 0.075 | 0.029 | 0.05 | 14$^b$ | 10,765$^b$ |

**Notes.** The observations were centered on RY Tau using target coordinates (J2000) R.A. = 04$^h$21$^m$57.5$^s$41, decl. = +28$^\circ$26′35″57″. All exposures were obtained in ACCUM mode with the $52'' \times 0''/2$ slit aligned along the optical jet axis ($PA_{\text{APER}} = 112^\circ$45'). STIS target acquisition centers the source in the slit to an accuracy of $0''/01 (2\sigma)$. No additional peakup was performed. A three-step STIS_ALONG_SLIT dither pattern was used with a $0''/275$ step size. The spectral resolution for MAMA first-order modes is 1.5 pixels (FWHM) at 1500 Å, equivalent to $15 \text{ km s}^{-1}$ (FWHM). The STIS G140M wavelength accuracy from calibration studies expressed as the mean difference between observed (Gaussian-fitted) and laboratory wavelengths of selected emission lines is $0.13 \pm 0.14$ (1σ) MAMA pixels (Sonnenbichler 2015). At 1500 Å this equates to $1.3 \pm 1.4$ km s$^{-1}$. Instrument properties are from the STIS Data Handbook unless otherwise noted.

$^a$ For tilt corresponding to central wavelength, $\lambda_c = 1550 \text{ Å}$.

$^b$ Exposure OCKF01060 (815 s) was not usable and is excluded from totals.

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5 Accessible in electronic form at [http://www.chiantidatabase.org/chianti_line_list.html](http://www.chiantidatabase.org/chianti_line_list.html).

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Figure 1. STIS MAMA G140M Gaussian-smoothed 2D spatially resolved spectral-image of the RY Tau jet created by summing individual exposures showing extended C IV (1548.2/1550.8 Å) emission. The horizontal axis is wavelength (Å) and the vertical axis is spatial offset from star along the jet (arcsecs). The horizontal line marks the position of the stellar trace within an uncertainty of ±0.2 MAMA pixels. For the 1548.2 Å component, the zero-velocity tick mark corresponds to 1548.29 Å after correcting for the star’s heliocentric radial velocity ($v_{hel}$ = +18 km s$^{-1}$). STIS spatial resolution is ≈0.0725 per two-pixel spatial resolution element. Contour levels are 0, 5, 145, 250, and 345 per two-pixel spatial resolution element. The uncertainty in the location of the stellar trace on the detector is of low significance compared to the ±0.2 pixel uncertainty in the location of the stellar trace on the detector. The spectrum is dominated by the bright broad blueshifted C IV doublet lines (Table 3). However, as noted above, several slightly blueshifted fluorescent H$_2$ lines are also detected (Table 4). In addition to the conspicuous H$_2$ lines visible in Figure 2, the blue wing of C IV 1548 Å shows a narrow peak that is due to H$_2$ R(3)-8 emission and C IV 1551 Å may contain a weak contribution from H$_2$ P(8)2–8. Also visible in the G140M spectrum is a feature at rest-frame wavelength 1533.4 ± 0.04 Å identified as Si II λ1533.43 Å. Fainter emission from the Si II line at λ1533.43 Å may also be present.

Figure 2 zooms in on the C IV doublet in the G140M 1D on-source spectrum. Both lines are broad and noticeably asymmetric. Trial fits of each line with a simple one-component Gaussian model begin to reproduce the overall broad shapes, but residuals remain at the wavelengths expected for H$_2$ R(3)-8 and P(8)2–8. Adding narrow low-velocity Gaussians with velocities and widths fixed at $-9$ km s$^{-1}$ and FWHM = 44 km s$^{-1}$ based on mean values of other H$_2$ lines in the spectrum (Table 4) recovers the excess and results in a reasonably good first approximation of the overall doublet shape (Figure 3). The two H$_2$ lines that overlap C IV in the on-source spectrum contribute only 6% to the observed (absorbed) flux in the wavelength range spanned by the C IV doublet and most of this comes from the R(3) 1–8 line.

Line widths of FWHM = 304 ± 26 km s$^{-1}$ are needed to reproduce the broad C IV lines, which is well in excess of that expected from stellar rotation at $v_{sin}$ = $52$ ± 2 km s$^{-1}$ (Petrov et al. 1999). As a result of the five MAMA pixel spatial binning, the spectrum extracted on the stellar trace also captures emission from the inner jet ($<9.7$ au) which undoubtedly contributes to the line broadening. The Gaussian-fit centroids of the C IV lines in the stellar trace spectrum are blueshifted to $-65$ ± 10 km s$^{-1}$. However, this value cannot be considered a reliable flow velocity because of the asymmetric line shapes.
and blending. In addition, the flux ratio of the C IV doublet lines in the stellar trace spectrum is significantly less than the value $F_{1548}/F_{1551} = 2$ expected for optically thin emission (Table 3), so optical depth effects may be important near the star. A similar conclusion was reached by Lamzin (2000). More reliable velocities are obtained from off-source spectra of the jet where the C IV lines are narrower and well-modeled as single-component Gaussians (Section 3.4).

Even though there is little doubt that the spectrum extracted along the stellar trace includes C IV emission from the inner jet near the star, it is not obvious that the star itself contributes. There is no significant peak at the stellar radial velocity in the broad C IV line profile shown in Figure 3. Nevertheless, estimates of the C IV flux contributed by the inner unresolved jet to the on-source spectrum are significantly less than the measured flux, so there is little doubt that the star itself is contributing (Section 3.4).

We compared the C IV doublet flux in 14 exposures with individual exposure times of 10–14 minutes acquired over a timespan of 7.8 hr. No deviations of greater than 1.9σ with respect to the mean were found but low-level flux variations of
up to $\approx 20\%$ cannot be ruled out because of the lower S/N in spectra of individual exposures as compared to their sum. Because the C IV emission is extended on a spatial scale of at least one arcsecond, the measured flux depends on the aperture size or the spatial bin width used in STIS spectral extractions and comparisons with flux measurements from previous studies are not straightforward. However, we note that the observed flux measured in a total exposure spectrum centered on the stellar trace and using a spatial binsize of $2''$ to capture the central source and essentially all of the detected jet emission out to offsets of $\pm 1''$ is $F_{\text{C IV, absorbed}}^{1548+1551} = (8.65 \pm 0.58) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ ($H_2$ subtracted). For comparison, the value obtained by IUE was $F_{\text{C IV, absorbed}} = (8.7 \pm 0.3) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (Valenti et al. 2000). The agreement is remarkably good, considering that most of the IUE observations were obtained in the 1980s.

The feature in Figure 2 identified as Si II deserves further comment. This line was also listed as a detection in the Lyman-alpha profile of BP Tau analyzed by Lamzin et al. (2002), although this was followed by a comment. This line was also listed as a detection in previous studies of RY Tau, e.g., Ardila et al. (2002).

3.3. Extinction and C IV Luminosity

The intrinsic (unabsorbed) C IV line flux and luminosity are quite uncertain due to discrepancies in the value of $A_V$ determined from different color indices (Calvet et al. 2004) and subleties in the far-UV extinction law toward dark clouds such as Taurus (Fitzpatrick & Massa 1988; Cardelli et al. 1989; Whittet et al. 2004). Previous UV studies of RY Tau have adopted different stellar extinction values including $A_V = 0.29$ (Ardila et al. 2002), 0.55 (Gómez de Castro & Verdugo 2007), 0.6–1.3 (Lamzin 2000), 1.0–1.3 (Petrov et al. 1999), 1.8 (Kenyon & Hartmann 1995) and 2.2 $\pm 0.2$ (Calvet et al. 2004). The latter value is clearly larger than the others, but is nevertheless consistent with independent estimates based on X-ray absorption (Skinner et al. 2016). Assuming an extinction ratio $A_{1550}/A_V \approx 2.6$ (Calvet et al. 2004), our absorbed fluxes convert to unabsorbed values according to $F_{\text{C IV,unabsorbed}} = 10^{d/0.4} F_{\text{C IV,absorbed}}$. At $d = 134$ pc the intrinsic line luminosity is $L_{\text{C IV}} = 2.14 \times 10^{42} F_{\text{C IV,unabsorbed}}$ erg s$^{-1}$. If the extinction is at the high end of the range of values in the literature ($A_V \approx 2$) then the absorbed line flux for the star-jet out to offsets of $\pm 1''$ of $F_{\text{C IV,absorbed}}^{1548+1551} = 8.65 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ converts to an intrinsic (unabsorbed) luminosity $L_{\text{C IV}}^{\text{star-jet}} \sim 2 \times 10^{34}$ erg s$^{-1}$, which is comparable to the X-ray luminosity of RY Tau determined from Chandra and XMM-Newton observations (Table 1). The above derivation assumes that $A_V$ is the same for the star and the jet out to a separation of $1''$.

3.4. Spectra Extracted along the Jet

Figure 4 shows the C IV doublet in 1D total-exposure spectra extracted at an offset of $0''29$ (10 MAMA pixels) from the star along the blue and redshifted jets using a spatial bin width of $0''145$ (five pixels). These spectra capture emission at offsets of $0''29 \pm 0''0725$ (38.9 $\pm$ 9.7 au) along the jets. The lines in the blueshifted jet provide higher S/N and more reliable fit parameters. As is evident from the figure, the C IV lines are narrower and more symmetric (nearly Gaussian) than in the on-source spectrum. There is very little $H_2$ contamination at this offset. $H_2$ line fluxes are down by more than an order of magnitude compared with the on-source spectrum and are negligible. Gaussian fits of the C IV line at an offset of $0''29$ in the blueshifted jet give a velocity that is $9\%$ larger than that of the corresponding redshifted jet, but the blue- and red-jet velocities agree to within the measurement uncertainties (Table 3). Thus, we find no evidence for a significant velocity asymmetry in the jet at an offset of $0''29$ (39 au). The ratio of observed fluxes in the doublet lines in the spectra extracted at this offset is consistent with the value $F_{1548}/F_{1551} = 2$ expected for optically thin emission.

Figure 5 plots the absorbed C IV flux (sum of the doublet components) in the blueshifted jet as a function of projected offset from the star. The flux decreases toward larger offsets and the falloff is well fitted by a simple exponential model at offsets $\geq 0''29$. The jet flux cannot be reliably measured at small offsets $<0''29$ or at offsets beyond $1''$. However, extrapolating the exponential fit back to the star gives a predicted blue-jet flux $F_{\text{C IV,blue-jet}}^{\text{absorbed}}$ (offset $= 0''$) $= 1.51 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. We assume that the red jet contributes equally to the C IV flux in the on-source spectrum, but this is probably an overestimate as the red-jet flux is weaker than the blue jet at offsets away from the star (Table 3). We thus expect an on-source C IV flux contribution from the blue and red jet lobes combined of no more than twice the above value, namely $F_{\text{C IV,absorbed}}^{\text{offset} = 0''} = 3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. But the absorbed flux measured in the on-source spectrum extracted using a five MAMA pixel spatial bin width is $F_{\text{C IV,absorbed}}^{\text{offset} = 0''}$ $= 5.41 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (Table 3). The additional C IV flux in the on-source spectrum above that expected from the inner jet lobes is very likely due to the star itself. This result is not surprising, as C IV emission is almost always detected in CTTS, even those without jets (Valenti et al. 2000; Ardila et al. 2013).

Figure 6 shows the radial velocity in the blueshifted jet as a function of offset from the star as measured by the centroid of the brighter C IV 1548.2 Å line. There is a clear decrease in jet speed toward larger offsets and this decrease is well approximated by a linear fit $v_{\text{blue-jet}} = 71.46 \pm (21.20) \times$ offset (arcsec) $- 164.7 \pm (11.0)$ km s$^{-1}$ for offsets in the range 0''29–0''73 (39–98 au).

4. Discussion

4.1. Jet Mass-loss Rate

The jet mass-loss rate for a fully ionized jet is

$$M_j = \mu m_H n_e v_j A,$$  

(1)

where $\mu \approx 1.24$ is the mean atomic weight (amu) per nucleus for gas with cosmic abundances, $m_H$ is the proton mass, $n_e$ is the average electron density in the jet, $v_j$ is the (deprojected)
Figure 4. G140M C IV total-exposure spectra of the RY Tau jet showing flux density vs. observed wavelength. The spectra were extracted at an offset of 10 MAMA pixels using a spatial bin full width of five pixels, capturing jet emission at offsets of $0''725 \pm 0''725$ (38.9 ± 9.7 au) from the star. The spectra have been rebinned by a factor of two in wavelength. Zero velocities correspond to 1548.29 and 1550.87 Å after correcting for the star’s heliocentric radial velocity ($v_{rad} = +18$ km s$^{-1}$). Left: blueshifted (approaching) jet. Line centroids give velocity shifts of $-143 \pm 7$ km s$^{-1}$ (1548 Å component) and $-129 \pm 13$ km s$^{-1}$ (1551 Å component). Line widths are FWHM = 127 km s$^{-1}$. The observed (absorbed) integrated line fluxes are $F_{1548} = 4.00 \times 10^{-2}$ and $F_{1551} = 1.58 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. Right: redshifted (receding) jet. Line centroids give velocity shifts of $+130 \pm 15$ km s$^{-1}$ (1548 Å component) and $+120 \pm 13$ km s$^{-1}$ (1551 Å component). Line widths are FWHM = 127 km s$^{-1}$. The observed (absorbed) integrated line fluxes are $F_{1548} = 1.18 \times 10^{-15}$ and $F_{1551} = 0.53 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$.

Figure 5. Absorbed C IV flux (sum of the 1548 and 1551 Å components) vs. projected offset from RY Tau along the blueshifted jet. Fluxes were measured in spectra extracted using a spatial bin width of five MAMA pixels (full width = $0''145$) except for the last data point centered at offset = $0''93$, which was extracted using a bin width of nine pixels (full width = $0''26$) to bring out faint jet emission. The data point for the spectrum extracted on the stellar trace (offset = 0") contains emission from the star and the unresolved inner blue and redshifted jets out to offsets of $\pm 0''725$ (±9.7 au). The solid line is an exponential fit of the five blue-jet flux data points and gives Absorbed C IV Flux = $A \exp(-(offset - B)/C)$, where the offset (arcsecs) is taken as a positive value and best-fit parameters are $A = 0.1977$, $B = 0.5768$, and $C = 0.2838$. Integrating the exponential model over the range $0''-1''$ gives a total blue-jet flux $F_{CIV}^{blue,jet} = 4.15 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. Extrapolating the model back to the star gives a blue-jet flux at the zero offset position of $1.51 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

jet velocity, and $A$ is the cross-sectional area of the jet. For simplicity, we consider the blue-jet lobe within $1''$ of the star, where our velocity measurements are reliable. Within the inner arcsecond the jet is well collimated with nearly constant deconvolved width FWHM $\approx 0''18$ (Agra-Amboage et al. 2009; Coffey et al. 2015). We thus assume a cylindrical jet with cross-sectional area $A = 1.02 \times 10^{-29}$ cm$^2$ at a distance of 134 pc. At an offset of $0''5$ from the star the radial jet velocity is $\approx 129$ km s$^{-1}$ (Figure 6). We assume a jet inclination relative to the line-of-sight $i_{jet} = 61^\circ \pm 16^\circ$ as determined by Agra-Amboage et al. (2009). For comparison, we note that Isella et al. (2010) used thermal dust models based on multi-wavelength millimeter data to constrain the disk rotation axis inclination to be in the range $i_{disk} = 66^\circ \pm 2^\circ$ (1.3 mm) – $71^\circ \pm 6^\circ$ (2.8 mm). For our adopted jet inclination angle, the deprojected jet velocity is $v_{jet} \approx 266^{+307}_{-257}$ km s$^{-1}$, where the uncertainty is due only to the uncertainty in $i_{jet}$ and the much smaller uncertainty (<10%) in the jet velocity measurement.
from the C IV centroid shift is ignored. Substituting these numbers into Equation (1) gives

\[ M_{\text{jet,blue}} = 8.9 \times 10^{-10} \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right) M_\odot \text{ yr}^{-1}. \]  

To estimate \( n_e \), we use the expression for the C IV volume emission measure (EM),

\[ EM_{\text{C IV}} = n_e^2 f \nu L_{\text{C IV}} \Lambda_{\text{C IV}}^{-1}, \]  

where \( \nu \) is the volume filling factor of the C IV plasma (0 < \( f \) \( \leq \) 1), \( L_{\text{C IV}} \) is the unabsorbed C IV luminosity, and \( \Lambda_{\text{C IV}} = 6.8 \times 10^{-23} \text{ erg s}^{-1} \text{ cm}^{3} \) is the volumetric cooling rate for C IV determined by Schneider et al. (2013a). As we have noted (Section 3.3), the value of \( L_{\text{C IV}} \) for RY Tau is subject to uncertainties in \( \Lambda_{\text{C IV}} \). Assuming \( \Lambda_{\text{C IV}} \approx 2 \) and using the integrated C IV line flux within the inner arcsecond of the blue jet (Figure 5), we obtain \( EM_{\text{C IV}} = 1.57 \times 10^{53} \text{ cm}^{-3} \) and \( n_e \sqrt{\nu} = 2.6 \times 10^4 \text{ cm}^{-3} \). Leaving \( f \) as a free parameter gives \( M_{\text{jet,blue}} = (2.3 \times 10^{-9}) / \sqrt{\nu} M_\odot \text{ yr}^{-1} \). This value is consistent with the value \( M_{\text{jet,blue}} = (1.6-26) \times 10^{-9} M_\odot \text{ yr}^{-1} \) obtained by Agra-Amboage et al. (2009) using high spatial resolution [O I] \( \lambda 6300 \) A spectral-images. For a symmetric jet, the derived mass-loss rate for blue and red jet lobes combined would be about twice the above value. The main uncertainties in the above calculation are the deprojected jet velocity \( v_{\text{jet}} \) (\( i_{\text{jet}} \)-dependent), \( L_{\text{C IV}} \) (\( A_v \)-dependent), and the volume filling factor \( f \). In addition, we have assumed a fully ionized jet, and if that is not the case, then Equation (1) would need to be modified as discussed by Hartigan et al. (1994). Considering the uncertainties, the above can only be regarded as an order-of-magnitude estimate of the jet mass-loss rate. For comparison, the mass-loss rate of RY Tau estimated by Kuhı (1964) using a spherically symmetric isotropic wind model was \( M_\odot = 3.1 (1.3-5.0) \times 10^{-8} M_\odot \text{ yr}^{-1} \), where the range in parentheses reflects values obtained using different spectral lines. A more recent estimate of the wind mass-loss rate by Petrov et al. (2017) gives \( M_{\text{wind}} = 2 \times 10^{-9} M_\odot \text{ yr}^{-1} \).

### 4.2. Jet Heating Models

The physical process which heats the jet and where the heating occurs are not yet well understood. The STIS observation discussed above reveals warm jet plasma from C IV emission to within a few tenths of an arcsecond of RY Tau, so some jet heating must take place close to the star. The new STIS data, along with information on jet morphology obtained in earlier studies, allow some constraints on heating mechanisms to be obtained as discussed below.

**Base-heated Jet.** If heat input is restricted to the jet base near the star, then it is launched hot and cools by different processes such as radiation and expansion as it flows outward. Because the width of the RY Tau jet remains nearly constant within \( \sim 150 \text{ au} \) (\( \sim 1'' \)) of the star (Agra-Amboage et al. 2009), we assume that radiative cooling is the dominant process. Any additional adiabatic cooling due to expansion would shorten the cooling times derived below, which should therefore be regarded as upper limits.

The radiative cooling time is

\[ \tau_{\text{rad}} = \frac{3kT}{n_e \Lambda(T)}. \]  

We first assume a jet-base temperature \( T_{\text{jet}} \sim T_{\text{C IV}} \sim 10^5 \text{ K} \), but this should be considered a lower limit, and the possibility of a higher jet-base temperature is considered below. For a solar-abundance plasma we use \( \Lambda(T = 10^5 \text{ K}) = 6.5 \times 10^{-22} \text{ erg s}^{-1} \text{ cm}^{3} \), of which about one-third comes from carbon-cooling transitions, primarily C III (977 Å) and C IV (Smith et al. 2001; Foster et al. 2012; Lykins et al. 2013). Inserting this value into Equation (4) along with \( n_e \sqrt{\nu} = 2.6 \times 10^4 \text{ cm}^{-3} \) (Section 4.1) gives a radiative cooling time \( \tau_{\text{rad}} = 0.077 \sqrt{\nu} \text{ year} \).

The distance traversed by the jet during the cooling time depends on the (deprojected) jet velocity after taking into account the jet inclination angle \( i_{\text{jet}} \) relative to the line of sight. The jet inclination is not well determined for RY Tau, but previous work suggests \( i_{\text{jet}} = 61^\circ \pm 16^\circ \) (Agra-Amboage et al. 2009). At an offset of \( 0''5 \) from the star, which we take as representative, the radial velocity of the blue jet is \( 129 \text{ km s}^{-1} \) (Figure 6). This corresponds to a deprojected velocity \( v_{\text{jet}} = 266 (182-573) \text{ km s}^{-1} \) and a projected (tangential) velocity \( v_{\text{jet}} = 233 (159-501) \text{ km s}^{-1} \), where the range in parentheses reflects the uncertainty in \( i_{\text{jet}} \). At this speed, the time required for the jet to traverse a projected distance of \( 134 \text{ au} \) (\( 1'' \)) is \( 2.7 (1.2-4.0) \text{ years} \). But during the cooling time the jet traverses a projected distance of only \( d_t = 3.8 (2.6-8.1) \text{ au} \). This value is much less than the distance \( d_t \sim 134 \text{ au} \) (\( 1'' \)), to which the blueshifted jet is actually detected in C IV (Figure 1).

The above discrepancy could be resolved if the radiative cooling time is longer than estimated above, or if the jet undergoes additional heating as it flows outward. Possible additional heating mechanisms are discussed below. A longer radiative cooling time could be achieved if the jet base temperature is significantly higher than the value \( T_{\text{jet}} \sim T_{\text{C IV}} \sim 10^5 \text{ K} \) assumed above, or if \( n_e \) is lower than assumed. Another question that may be relevant to the above discrepancy is whether the jet plasma is in collisional ionization equilibrium (CIE).

Some models assume temperatures at the jet base of a few MK as in the disk corona heating model of Takasao et al. (2017). Their analysis of the DG Tau jet adopted a jet-base temperature \( T_{\text{jet}} = 3.4 \text{ MK} \) based on the X-ray observations of Güdel et al. (2008). The jet-base temperature of RY Tau is not known, but a value of at least \( 3-4 \text{ MK} (kT \sim 0.26-0.34 \text{ keV}) \) would be needed to produce detectable jet thermal X-ray emission above Chandra’s low-energy limit. Such emission may be present at offsets out to \( \sim 1''7 \) from the star along the blueshifted jet (Figure 4 of Skinner et al. 2011). However, Chandra’s angular resolution (FWHM \( \approx 0.5'' \)) is insufficient to spatially distinguish between X-rays originating near the jet base within a few au of RY Tau or further out in the jet.

Assuming a jet-base temperature \( T_{\text{jet}} \sim 3 \text{ MK} \) at the low end of Chandra’s detection range gives a radiative cooling time (Equation (4)) of \( \tau_{\text{rad}} = 6.9 \sqrt{\nu} (n_e/10^4 \text{ cm}^{-3}) \) years. Here, \( f_e \) is the volume filling factor of X-ray emitting plasma in the jet, and we have used \( \Lambda = \Lambda_\odot (T = 3 \text{ MK}) = 5.7 \times 10^{-23} \text{ erg s}^{-1} \text{ cm}^{3} \) for solar-abundance plasma (Foster et al. 2012). To produce soft X-ray emission out to a projected
(tangential) separation of 1"7 from the star, the cooling time would need to be at least $\tau_{\text{rad}} \sim 4.6$ years for $v_{\text{jet}} = 266$ km s$^{-1}$. This would be the case if $n_x \lesssim 1.5 \times 10^5$ cm$^{-3}$. This electron density is consistent with that derived above using the C IV luminosity provided that $f_e \gtrsim 0.03$.

As is clear from the above, the ability of the base-heated jet model to produce soft X-rays at offsets $>1''$ for a given jet speed depends critically on the jet plasma cooling time. The radiative cooling time is proportional to $T_{\text{jet}}/n_x \Lambda(T)$, but neither $T_{\text{jet}}$ nor $n_x$ is tightly constrained by observations. For the above estimate, we assumed $T_{\text{jet}} \sim 3$ MK but if $T_{\text{jet}} \sim 6$ MK then $\tau_{\text{rad}}$ increases by a factor of 2.5 for a given $n_x$. Non-radiative cooling from processes such as expansion may also contribute but has been neglected above since the optical jet width shows little change at the projected offsets of interest here, and reliable measurements of the width of the faint X-ray jet versus projected separation are not available.

Collisional ionization equilibrium. A difference between the observed spatial extent of the C IV jet and that predicted from the radiative cooling time $\tau_{\text{rad}}$ could occur if the jet plasma is not in CIE. Departures from CIE occur when plasma is rapidly heated (e.g., by shocks) or cooled on a timescale much shorter than the time $\tau_{\text{cie}}$ for ionization equilibrium to be restored. Under non-CIE conditions, the plasma is in a transient state during which it radiates at a temperature that is decoupled from ionization balance (Mewe 1999).

The timescale $\tau_{\text{cie}}$ required for a given element to reach CIE is inversely proportional to electron density $n_x$, and has a complex electron-temperature dependence arising from differences in ionization and recombination rates of various ions (Figure 1 of Smith & Hughes 2010; Mewe 1999). Without accurate estimates of the RY Tau jet temperature and electron density, we cannot reach a firm conclusion as to whether it is in CIE, but a preliminary assessment is possible based on order-of-magnitude estimates.

If the jet temperature is $T \approx 10^5$ K, the metals that would take the longest time to reach CIE are C and Al (Smith & Hughes 2010). At this temperature, the time required for all C ions to be within 90% of their CIE value is $\tau_{\text{cie,c}} \approx 3.8/\sqrt{f} \times 10^4$ cm$^{-3}$ years. Using our estimate $n_x \sqrt{f} = 2.6 \times 10^4$ cm$^{-3}$ (Section 4.1) gives $\tau_{\text{cie,c}} \approx 1.5$ years. As noted previously, the time required for the jet to propagate out to the C IV-traced distance of 134 au (1") is $\tau_{\text{jet}} = 2.7 (1.2-4.0)$ years. Thus, if the jet temperature is $T \approx 10^6$ K, then CIE appears likely. If the jet is at X-ray emitting temperatures $T \gtrsim 3 \times 10^6$ K, then the value of $\tau_{\text{cie,c}}$ determined by Smith & Hughes (2010) is at least an order of magnitude less than at $10^5$ K, and the case for CIE is strengthened. Based on the above estimates, the case for invoking non-CIE conditions in the RY Tau jet does not look compelling.

Hot plasmoids. Ejection of hot plasmoids during powerful stellar X-ray flares could produce high-temperature plasma in discrete structures offset from the star. This picture is reminiscent of solar coronal mass ejections and has been discussed in the context of large X-ray flares from protostars by Hayashi et al. (1996).

In their picture, discrete plasmoids at or near coronal flare-loop temperatures are ejected at high velocities of several hundred km s$^{-1}$, but in extreme cases may approach $\sim 1000$ km s$^{-1}$. We assume that the ejected plasmoid is at temperature $T_{\text{plasmoid}} \sim 10^6$ K since superhot X-ray flares at such temperatures have been detected in RY Tau (Skinner et al. 2011).
is magnetically confined, then the magnetic pressure must exceed the gas (plasma) pressure, \( P_{\text{gas}} = \beta P_{\text{mag}} \) where \( 0 < \beta < 1 \). Specifically, \( n_{\text{tot}} k T_{\text{jet}} = \beta (B_{\text{jet}}/8\pi) \) where \( n_{\text{tot}} \) is the total particle density in the jet, \( k \) is Boltzmann’s constant, and \( T_{\text{jet}} \) is the jet temperature. We assume \( T_{\text{jet}} \sim T_{\text{CIV}} \sim 10^5 \) K as above, but as already noted, this should be taken as a lower limit.

For solar-abundance plasma with fully ionized H and He, we get \( n_{\text{tot}} \approx 1.92 n_c \approx (5 \times 10^4)/\sqrt{f} \) when using the value of \( n_c \) obtained in Section 4.1. This gives \( B_{\text{jet}} = 4/(f^{0.25} \beta^{1.5}) \) mG. For marginal confinement (\( \beta = 1 \)), \( B_{\text{jet}} = 4/f^{0.25} \) mG, but strong-confinement values \( \beta \ll 1 \) are typically used in magnetic jet simulations.

To obtain a second estimate of \( B_{\text{jet}} \), we use the canonical formula for magnetized young stellar jets proposed by Hartigan et al. (2007):

\[
\frac{B_{\text{jet}}}{15 \mu G} = \left( \frac{n_{\text{tot}}}{100 \text{ cm}^{-3}} \right)^{0.85}.
\]

Using \( n_{\text{tot}} \approx (5 \times 10^4)/\sqrt{f} \) for RY Tau as above gives \( B_{\text{jet}} \approx 3/f^{0.425} \) mG, similar to that obtained using equipartition arguments.

Adopting a deprojected jet speed \( v_{\text{jet}} \approx 266 \text{ km s}^{-1} \) at an offset of 0.75 from the star as a representative value and a jet radius \( r_{\text{jet}} \approx 0.09 \) au for the inner arcsecond of the RY Tau jet, the magnetic energy in the jet is \( L_{\text{mag}} = 10^{44} (B_{\text{jet}}/5 \mu G)^2 \text{ erg s}^{-1} \), where we have used the results of Schneider et al. (2013a) but have normalized to a weaker field strength of 5 mG. Using this result, the minimum required field strength to account for the integrated blue-jet C IV luminosity (Figure 5) is \( B_{\text{jet}} \sim 11 \text{ mG} \) if \( A_v \approx 2 \) (i.e., \( L_{\text{CIV,blue-jet}} = 1.1 \times 10^{31} \text{ erg s}^{-1} \)). This field strength is about 50 times greater than that determined for the HH 80–81 jet by Carrasco-González et al. (2010).

4.3. Fluorescent H2 Lines

Fluorescent H2 lines are commonly present in the FUV spectra of TTS and are thought to be pumped mainly by wings of the stellar H Ly\( \alpha \) line. Detailed studies of fluorescent H2 emission in selected samples of TTS with the \textit{HST} were carried out by Ardila et al. (2002) using the GHRS and by France et al. (2012) using the Cosmic Origins Spectrograph and STIS. Their results revealed that the H2 lines in cTTS are broadened to typical values FWHM \( \approx 40 \pm 20 \text{ km s}^{-1} \), with velocities ranging from 0 km s\(^{-1}\) (i.e., the line centroid is centered at the stellar radial velocity) to values of a few tens of km s\(^{-1}\).

The H2 lines that we detect for RY Tau are blueshifted by an average of \( -9 \pm 1 \text{ km s}^{-1} \) and moderately broadened to an average width FWHM \( = 44 \pm 2 \text{ km s}^{-1} \). The brightest H2 line is R(11) 2–8 as shown in Figure 7. The velocity shifts are significantly larger than the STIS G140M wavelength calibration uncertainty (Table 2). The line broadening is also significant compared with the STIS G140M instrumental resolution of FWHM \( \approx 15 \text{ km s}^{-1} \) at 1500 Å. The fitted H2 line widths are well above that expected from thermal broadening and turbulence, as has generally been found for the larger samples of TTS analyzed in the studies referenced above. Thus, bulk motion of molecular gas is implied.

Several different origins of the fluorescent H2 lines in cTTS have been proposed. In the sample analyzed by Ardila et al. (2002), the H2 line centroids in most stars were blueshifted and line formation in outflows was considered to be the most likely explanation. In the sample studied by France et al. (2012), some cTTS showed H2 lines with non-zero velocities suggestive of outflows, a good example being the jet-driving cTTS RW Aur A. On the other hand, no significant velocity shift was detected in some cTTS and it was proposed that their fluorescent H2 emission originates in a rotating disk. A detailed study of the jet-driving cTTS DG Tau using STIS G140M (Schneider et al. 2013a) and \textit{HST} FUV imaging (Schneider et al. 2013b) revealed H2 emission close to the star near the approaching jet axis, as well as extended emission fanning out into a wide-angle conical-shaped structure. The wide-angle emission was attributed to a disk wind. In view of the various results and interpretations above, it seems likely that different regions near the star can contribute to fluorescent H2 emission. The complex H2 morphology of DG Tau seen in \textit{HST} FUV images supports this.

The remarkable similarity in blueshifted velocities and widths of the H2 lines we detect in RY Tau, along with the faint blueward spatial extension seen in brighter H2 lines (Section 3.1), is indicative of a low-velocity molecular outflow approaching the observer. The blueshifted centroids are at odds with the broadened unshifted lines expected for H2 formation in a rotating disk. The spatial morphology of the outflowing gas is not well determined by the narrow 0′/2 \textit{STIS} slit, but H2 emission is certainly present within 0′/0725 (9.7 au) of the star (Figure 2). In addition, the R(11) 2–8 and P(5) 1–8 lines are faintly visible in G140M spectra extracted at a blueward offset along the jet of 0′/29 ± 0′/0725 (38.9 ± 9.7 au), so the presence of H2 out to a projected distance of at least 30 au from the star is assured. The extended blueshifted H2 emission may originate in molecular gas that is being swept outward by the jet, possibly similar to the H2 emission detected near the approaching jet axis of DG Tau (Figure 3 of Schneider et al. 2013b). High-resolution FUV images of RY Tau are needed to further clarify the spatial structure of the H2 emission, especially away from the jet axis where extended conical-shaped structure has been seen in DG Tau.

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**Figure 7.** RY Tau H2 R(11)2–8 line at full STIS G140M spectral resolution (i.e., no rebinning in wavelength) from a spectrum extracted along the stellar trace using a spatial bin width of 5 MAMA pixels (full width = 0′/145). The spatial width captures emission out to offsets of ±0′/0725 (±9.7 au) from the star along the jet. The velocity scale is relative to the star’s rest frame and zero-velocity corresponds to 1555.98 Å for a heliocentric stellar radial velocity of +18 km s\(^{-1}\). The Gaussian fit gives a velocity of –7.7 ± 2 km s\(^{-1}\) and FWHM = 42 ± 3 km s\(^{-1}\).
5. Summary

The HST STIS observations presented here provide new information on RY Tau and its jet that help constrain jet-heating models. The main results of this study are summarized as follows:

1. Warm plasma ($T_{\text{CIV}} \sim 10^5$ K) traced by C IV emission is clearly detected in STIS 2D images out to a projected offset of 1″ (134 au) from the star along the blueshifted jet and out to 0′′75 (67 au) along the fainter redshifted jet. The C IV emission is traced inward to offsets of a few tenths of an arcsecond, implying that significant jet heating occurs close to the star.

2. The radial velocity in the brighter blueshifted jet is $-136 \pm 10$ km s$^{-1}$ at a projected offset of 0′′29 (39 au) and the jet speed decreases toward larger offsets. No significant difference in the radial velocity of the blue and redshifted jets is seen at an offset of 0′′29.

3. The mass-loss rate in the blueshifted jet is $\dot{M}_{\text{jet, blue}} = 2.3 \times 10^{-9} / \sqrt{f} M_\odot$ yr$^{-1}$, where $f$ is the volume filling factor of C IV plasma in the jet. This value is consistent with previous optical measurements.

4. Several fluorescent H$_2$ lines blueshifted to $-9 \pm 1$ km s$^{-1}$ are detected near the star. These lines evidently originate in a low-velocity molecular outflow, but additional high spatial resolution FUV images are needed to further clarify the outflow geometry.

5. Jet velocities determined from C IV centroids are high enough to account for warm C IV plasma by shocks in the inner jet at offsets of $<1″$. Soft X-rays due to shocks in the inner jet could also occur if the deprojected jet speed is near the high end of the range allowed by jet inclination uncertainties but extreme shock speeds $\gamma_i \approx \gamma_{\text{jet}}$ are required. At offsets beyond 1″ the extrapolated jet speed is too low to produce soft X-rays at energies above Chandra’s threshold. Thus, shocks alone do not provide a satisfactory explanation of the soft X-ray emission detected by Chandra at offsets $>1″$ along the blueshifted jet.

6. Other jet-heating mechanisms besides shocks seem necessary to produce soft X-ray emission along the jet. One possibility is that the jet is heated to X-ray temperatures near the base and is launched hot. The heating process is unspecified but could well involve magnetic processes in a magnetically active star like RY Tau. A recent study focusing on the DG Tau jet has magnetic processes in a magnetically active star like RY Tau. A recent study focusing on the DG Tau jet has

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Facility: HST/STIS.

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