CHANDRA AND XMM-NEWTON X-RAY OBSERVATIONS OF THE HYPERACTIVE T TAU RI STAR RY TAU

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Abstract

We present results of pointed X-ray observations of the accreting jet-driving T Tauri star RY Tau using Chandra and XMM-Newton. We obtained high-resolution grating spectra and excellent-quality CCD spectra and light curves with the objective of identifying the physical mechanisms underlying RY Tau’s bright X-ray emission. Grating spectra reveal numerous emission lines spanning a broad range of temperature superimposed on a hot continuum. The X-ray emission measure distribution is dominated by very hot plasma at T_hot ∼ 50 MK, but higher temperatures were present during flares. A weaker cool plasma component is also present as revealed by low-temperature lines such as O viii. X-ray light curves show complex variability consisting of short-duration (∼hours) superhot flares accompanied by fluorescent Fe emission at 6.4 keV superimposed on a slowly varying (∼one day) component that may be tied to stellar rotation. The hot flaring component is undoubtedly of magnetic (e.g., coronal) origin. Soft- and hard-band light curves undergo similar slow variability implying that at least some of the cool plasma shares a common magnetic origin with the hot plasma. Any contribution to the X-ray emission from cool shocked plasma is small compared to the dominant hot component but production of individual low-temperature lines such as O viii in an accretion shock is not ruled out.

Key words: accretion, accretion disks – stars: coronae – stars: individual (RY Tau) – stars: pre-main sequence – X-rays: stars

1. INTRODUCTION

Classical T Tauri stars (cTTS) are low-mass pre-main sequence stars that are accreting from disks and continue to be high-interest objects for their remarkable range of activity (Bertout 1989) and as potential host stars for nascent protoplanetary systems. They are intense X-ray emitters whose X-ray luminosities typically exceed that of the contemporary Sun by ∼2–3 orders of magnitude (Feigelson & Montmerle 1999). The intense X-ray emission heats and ionizes the inner disk, altering disk chemistry and influencing the physical environment in which planet formation occurs (Glassgold et al. 1997; Shang et al. 2002).

Early studies of cTTS suggested that their X-ray emission is dominated by magnetic (e.g., coronal) processes analogous to scaled-up solar activity (Feigelson & Montmerle 1999). This emission is often variable and can display huge magnetic reconnection flares characterized by rapid changes (∼hours to days) in the observed X-ray flux and elevated plasma temperatures reaching extreme values T > 100 MK.

However, more recent observational work has shown that other physical processes also contribute to the X-ray emission of cTTS. Cool plasma (T < 3 MK) that is thought to arise in the post-shock zone of an accretion shock at or near the stellar surface has been detected in a few cTTS, most notably TW Hya (Kastner et al. 2002; Stelzer & Schmitt 2004; Brickhouse et al. 2010). There is also accumulating evidence that faint soft X-rays are produced in collimated high-speed jets within a few arcseconds of the central star. Such cTTS X-ray jet sources include the well-studied object DG Tau (Güdel et al. 2005, 2008) and possible X-ray jet detections in RY Tau (Skinner et al. 2011; hereafter SAG11) and RW Aur (Skinner & Güdel 2014). X-ray jet emission was also observed following an optical outburst in the unusual pre-main sequence binary Z CMa (Stelzer et al. 2009). Soft X-ray emission that likely originates in shock-heated material has been reported in some Herbig–Haro objects of which a few examples are HH 2 (Pravdo et al. 2001), HH 80/81 (Pravdo et al. 2004), HH 154 (Favata et al. 2002, 2006; Bally et al. 2003), and HH 210 (Grosso et al. 2006).

X-ray jet emission is usually recognized in high-resolution images as ∼arcsecond-scale structure extending outward from the unresolved central star along one or (rarely) both of the optical jet axes. Chandra’s excellent spatial resolution has proven to be especially useful in identifying such faint extended jet structure. On the other hand, coronal and accretion shock X-ray emissions originate near the stellar surface and cannot be spatially resolved with existing X-ray telescopes. But analysis of individual emission lines in high-resolution X-ray grating spectra can potentially distinguish between cool dense plasma in accretion shocks (T ∼ few MK; n_e > 10^12 cm^-3) and hotter lower-density coronal plasma (typically n_e < 10^12 cm^-3), as clearly demonstrated in the case of TW Hya.

Relatively few cTTS are bright enough in X-rays to permit good-quality grating spectra to be acquired in reasonable exposure times. We identified the accreting jet-driving cTTS RY Tau as a promising candidate for grating spectroscopy on the basis of bright X-ray emission detected in a 2009 Chandra ACIS-S observation (SAG11). Moderate resolution CCD spectra revealed multi-temperature plasma consisting of a superhot flaring component (typical of coronal emission) and cooler plasma of uncertain origin. Deconvolved soft-band images showed some evidence of extension outward along the blueshifted optical jet.

We present here new X-ray observations of the cTTS RY Tau obtained with Chandra and XMM-Newton. These observations include the first high-resolution grating spectra of RY Tau as well as high-quality undispersed CCD spectra and X-ray light curves. Our main objective is to obtain a more
complete picture of the properties of the X-ray emitting plasma (i.e., temperature, electron density, emission measure (EM) distribution) in order to differentiate between hot magnetically confined plasma (e.g., coronal emission) and cooler plasma that may originate in shocks.

2. RY TAU

RY Tau is an optically variable cTTS lying in the Taurus dark cloud (Bertout et al. 1999). Its properties are summarized in Table 1. Its mass $M_{\ast} \approx 2 M_{\odot}$ is relatively high for a TTS and it rotates rapidly at $v_{\sin i} = 52 \pm 2 \text{ km s}^{-1}$ (Petrov et al. 1999). It is accreting from a disk (Schegerer et al. 2008; Agra-Amboage et al. 2009) and mass-loss is clearly evident in the form of a bipolar jet known as HH 938 (St.-Onge & Bastien 2008) and a wind (Gómez de Castro & Verdugo 2007). Optical images have traced the jet and associated Hα knots outward to a separation of $31''$ from the star along P.A. $\approx 295^\circ$ (measured east from north), and the fainter counterjet is visible out to $3.5''$ from the star. Binarity is suspected based on *Hipparchos* photocenter motions (Bertout et al. 1999) but no companion has yet been found (Leinert et al. 1993; Schegerer et al. 2008; Pott et al. 2010). Searches for periodic optical variability have reported periods of ~years but no stable short period of ~days that might be associated with stellar rotation has yet been confirmed (Bouvier et al. 1993; Ismailov & Adygézalzade 2012 and references therein; Zajtseva 2010).

3. SUMMARY OF PREVIOUS XMM-NEWTON AND CHANDRA OBSERVATIONS

2000: RY Tau was captured 8/5 off-axis in a 2000 September *XMM-Newton* observation targeted on HDE 283572 (51 ks; ObsId 0101440701). This archived observation was included in the *XMM-Newton* Extended Survey of the Taurus Molecular Cloud (XEST) as reported by Güdel et al. (2007b). RY Tau was cataloged as XEST source 21-038. Fits of its CCD spectra with an absorbed $2T$ thermal plasma model gave $N_H = 7.6 \times 10^{21} \text{ cm}^{-2}$, $kT_{\text{cool}} = 0.5 \text{ keV}$, $kT_{\text{hot}} = 3.2 \text{ keV}$, and $\log L_X(0.3-10 \text{ keV}) = 30.72 \text{ erg s}^{-1}$ ($d = 140 \text{ pc}$). No large-amplitude variability was reported.

2003: RY Tau was captured off-axis in a 2003 October *Chandra* ACIS-S/HETG grating observation targeted on HDE 283572 (ObsId 3756). The zero-order ACIS-S spectrum and light curve of RY Tau were analyzed by Audard et al. (2005) but the grating spectrum was not analyzed due to lack of reliable calibration for far off-axis sources. The $\approx 100$ ks X-ray light curve showed a slow decline punctuated by a short-duration low-amplitude flare. The ACIS-S spectrum was fitted with an absorbed two-temperature ($2T$) thermal plasma model with temperatures $kT_{\text{cool}} = 1.0 \text{ keV}$, $kT_{\text{hot}} = 3.9 \text{ keV}$, absorption $N_H = 5 \pm 1 \times 10^{21} \text{ cm}^{-2}$, subsolar metallicity $Z = 0.3 Z_{\odot}$, and X-ray luminosity $\log L_x = 30.88 \text{ erg s}^{-1}$ at $d = 140 \text{ pc}$. Fluorescent Fe emission was detected at $\approx 6.4 \text{ keV}$.

2009: We obtained a 56 ks observation with RY Tau on-axis using *Chandra* ACIS-S without gratings in 2009 December (ObsId 10991). The star was detected as a bright variable X-ray source (SAG11). An absorbed $2T$ thermal plasma model gave $N_H = 5.5 \times 10^{21} \text{ cm}^{-2}$, $kT_{\text{cool}} = 0.6 \text{ keV}$, $kT_{\text{hot}} = 4.8 \text{ keV}$, $Z = 0.25 Z_{\odot}$, and $\log L_x(0.2-10 \text{ keV}) = 30.67 \text{ erg s}^{-1}$ ($d = 134 \text{ pc}$). For comparison with the above studies, the latter value equates to $\log L_x = 30.71 \text{ erg s}^{-1}$ at $d = 140 \text{ pc}$. Deconvolved soft-band (0.2–2 keV) ACIS-S images revealed faint extended structure overlapping the inner bluish-shifted optical jet and traced out to a separation of $\approx 1''$ from the star. A known asymmetry in the *Chandra* point-spread function may contribute to some of the structure inside one arcsecond. Five other X-ray sources were detected within one arcminute of RY Tau but all were quite faint.

4. OBSERVATIONS AND DATA REDUCTION

The X-ray observations are summarized in Table 2.

4.1. XMM-Newton

The *XMM-Newton* data were obtained in a single observation spanning $\approx 31$ hr in 2013 August. The primary instrument was the Reflection Grating Spectrometer (RGS) which consists of two spectrometers (RGS1 and RGS2) with similar spectral coverage over the $\approx 0.35-2.5 \text{ keV}$ energy range but with some gaps.\(^4\) The RGS effective area in first order reaches a maximum of $\approx 50-60 \text{ cm}^2$ per RGS at $\approx 15 \text{ Å} (\approx 0.8 \text{ keV})$, thus providing better sensitivity at lower energies $\lesssim 1 \text{ keV}$ than the *Chandra* High Energy Transmission Grating (HETG). RGS first-order spectral resolution at $12 \text{ Å} (\approx 1 \text{ keV})$ is $\Delta \lambda \approx 0.055-0.07 \text{ Å}$ (FWHM). In addition, *XMM-Newton* provided CCD imaging spectroscopy from the European Photon Imaging Camera (EPIC) which was used with the medium optical filter. The EPIC consists of the pn camera and two nearly identical MOS cameras (MOS1 and MOS2; Turner et al. 2001). The EPIC cameras provide energy coverage in the range $E \approx 0.2-15 \text{ keV}$ with energy resolution (FWHM) at 1 keV of $\Delta E \approx 70 \text{ eV}$ (MOS) and $\Delta E \approx 100 \text{ eV}$ (pn).

Data were reduced using the *XMM-Newton* Science Analysis System (SAS vers. 13.5.0). Event files were time-filtered to remove data acquired during a background flare at the end of the observation, resulting in $\approx 90-100$ ks of usable exposure

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\(^4\) RGS1 lacks coverage in the range 10.6-13.8 Å (0.90–1.17 keV) which includes the Ne I He-like triplet. RGS2 lacks coverage in the range 20.0–24.1 Å (0.51–0.62 keV) which includes the O I He-like triplet. For further details on RGS see http://xmm.esac.esa.int/external/xmm_user_support/documentation/uhb/rgs.html.

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### Table 1

| Sp. Type | $M_{\ast}$ ($M_{\odot}$) | $V$ (mag) | $A_V$ (mag) | $L_{\ast}$ ($L_{\odot}$) | $L_{bol}$ ($L_{\odot}$) | $\log L_x$ (erg s$^{-1}$) | $\log M_{soft}$ ($M_{\odot}$ yr$^{-1}$) | $d$ (pc) |
|---------|--------------------------|-----------|-------------|-------------------------|-----------------------|--------------------------|---------------------------------|---------|
| F8 III–G3 IV | 1.7–2.0 | 9.3–11 | 2.2 ± 0.2 | 7.0–8.8 | 15.3 | 30.5–31.2 (v) | −7.3 ± 0.3 | 134 |

Note. Data are from Agra-Amboage et al. 2009; Calvet et al. 2004; Holtzman et al. 1986; Kenyon & Hartmann 1995; and Schegerer et al. 2008. The stellar luminosity $L_{\ast}$ and bolometric luminosity $L_{bol}$ are based on the values $L_{\ast} = 7.6-9.6 L_{\odot}$, and $L_{bol} = 16.7 L_{\odot}$, at $d = 140 \text{ pc}$ (Kenyon & Hartmann 1995; Calvet et al. 2004) and have been normalized to $d = 134 \text{ pc}$. The $L_{\ast}$ range is based on this work. Distance is from Bertout et al. (1999). Variable parameters are denoted by (v). Spectral type is uncertain (Holtzman et al. 1986).
per instrument (Table 2). EPIC spectra and energy-filtered light curves were extracted from a circular region of radius 20″ centered on the source and background was extracted from source-free regions near RY Tau. The SAS task bgsub produced edited RGS event files that excluded the high-background time interval. RGS response matrix files (RMFs) were generated using the SAS task rgsrmfgen. Spectra were analyzed with Sherpa in CIAO version 4.6 and with XSPEC version 12.8.2. Timing analysis was performed with XRONOS v. 5.22. XSPEC and XRONOS are included in the HEASOFT XANADU6 software package.

4.2. Chandra

The Chandra data were acquired with the HETG and ACIS-S detector array in 2014 October in two observations spanning ≈24 hr and ≈7 hr with an intervening gap of ≈18.5 hr (Table 2). The combined livetime of the two observations was 109.4 ks, of which 85.5 ks was obtained in the first observation. The nominal pointing direction and roll angle were nearly identical for the two observations. Five of the six CCDs in the ACIS-S array were enabled (chip S0 was turned off).

We analyzed dispersed first-order HETG spectra from the Medium Energy Grating (MEG) and High Energy Grating (HEG) as well as undispersed (zero-order) ACIS-S spectra and X-ray light curves. The data were processed using standard science threads in CIAO version 4.6 and associated calibration data from CALDB version 4.6.1.1. Our analysis is based on Level 2 event files provided by Chandra X-ray Center (CXC) standard processing.

The HETG2 provides spectral coverage over the ≈0.4–10 keV (≈1.3–30 Å) range. Background rejection is high in HETG because of event order discrimination by ACIS-S, in sharp contrast to the much higher background in XMM-Newton RGS spectra. In addition, HETG provides spectral coverage above 2.5 keV where RGS coverage is lacking and is thus crucial for diagnosing hot plasma. Spectral resolution in the first order is ∆λ ≈ 0.023 Å for MEG and ∆λ ≈ 0.012 Å for HEG. The separate +1 and –1 order MEG spectra were co-added for analysis, and similarly for HEG. The effective area of MEG is maximum between 1–2 keV and HEG is maximum between 2–3 keV. The effective area of both gratings is lower than RGS at energies <1 keV. The HEG has superior spectral resolution but the MEG provides more total counts and higher signal-to-noise ratio in first-order spectra for this observation. Our Chandra grating analysis thus emphasizes the MEG spectrum for the longer first exposure (ObsId 15722) when most of the source counts were accumulated.

The zero-order ACIS-S CCD spectra and X-ray light curves were extracted from a circular region of radius 2″ centered on the RY Tau source peak. Background is negligible. ACIS-S provides energy coverage from ≈0.4–10 keV and its intrinsic energy resolution is ∆E ≈ 120 eV (FWHM) at E = 1 keV. Unlike our previous 2009 Chandra ACIS-S observation (without gratings), no 0-order image deconvolution was performed for the new ACIS-S/HETG observation discussed here. The point-spread function needed to produce the deconvolved image is spectral-dependent and the spectrum varied considerably throughout the observation (Section 5.2). In addition, the gratings disperse a significant fraction of the incoming photons, especially at energies below 2 keV, thereby reducing the sensitivity in 0-order to any faint soft (<2 keV) extended X-ray jet emission at small offsets from the star.

5. RESULTS

5.1. X-Ray Light Curves and Variability

The XMM-Newton EPIC broad-band light curves (Figure 1, top) are clearly variable during the first half of the observation. Two flare-like outbursts occurred within the time interval 20–45 ks after the start of the observation. EPIC spectra extracted during these flare intervals (Section 5.2) give substantially higher mean plasma temperatures than obtained from spectra extracted after removing the flares. Energy-filtered pn light curves (Figure 1, bottom) show no significant variability in the very-soft-band (0.3–1 keV) but have a high probability of variability Pvar > 0.99 in the medium (1–2 keV) and hard (2–8 keV) bands. The medium-band light curve reveals a slow increase in count rate during the observation with an average rate of 82 ± 2 c ks−1 in the first half and 92 ± 2 c ks−1 in the second half. Flare-like variability is most obvious in the hard-band.

The Chandra ACIS-S 0-order light curves are also variable. As shown in Figure 2 (top left), a slow decrease in count rate occurred during the first 40 ks of the first observation (ObsId 15722), followed by a moderate slow increase. The slow decay and subsequent rise are clearly detected in the very-soft, medium, and hard energy bands (Figure 2 (bottom left)). An exponential fit of the decay portion of the broad-band (0.3–8 keV) ACIS-S light curve gives an e-folding time of 27.5 ks. The plasma temperature and X-ray flux decreased during the decay phase and then began to increase again after the light-curve minimum, as discussed further in Section 6.

The average count rate and plasma temperature were lower in the second Chandra observation (ObsId 17539). A slow decrease in the broad-band (0.3–8 keV) and hard-band (2–8 keV) count rates is clearly visible (Figure 2 (right)). There are insufficient counts to construct a separate very-soft-band (0.3–1 keV) light curve so a 0.3–2 keV band light curve was generated to search for low-energy variability. This light curve is nearly constant during the first half of the observation but declines during the second half (Figure 2 (bottom right)). The respective count rates in the first and second halves were
9.42 ± 0.89 c ks⁻¹ and 8.08 ± 1.86 c ks⁻¹ (1σ uncertainties). A χ² test applied to the second half of the observation gives a variability probability \( P_{\text{var}} = 0.60 \) which is suggestive of variability but not conclusive.

5.2. Undispersed CCD X-Ray Spectra

Figure 3 shows the XMM-Newton EPIC pn spectra, which provide higher count rates and better sensitivity at low energies than MOS spectra. Spectra for the flare and non-flare time intervals are overlaid. The flare spectrum extracted during the 25 ks flare interval (as marked in the bottom panel of Figure 1) is clearly harder as evidenced by elevated continuum emission above ∼2 keV. The ratio \( H/S \) of hard-band (2–8 keV) to soft-band (0.3–2 keV) EPIC pn counts during the flare segment was \( H/S = 1.10 \) as compared to \( H/S = 0.67 \) during the non-flare time interval. The Fe K line complex near 6.7 keV (Fe xxv) which originates in very hot plasma (maximum emissivity temperature \( T_{e,\text{max}} \approx 63 \) MK) is present in both the flare and flare-excluded segments. Interestingly, an emission feature at ∼6.4 keV is present in the flare spectrum (Figure 3 (bottom)). A Gaussian fit of this feature gives a centroid energy \( E = 6.395 \pm 0.005 \) (1σ) keV. This line is fluorescent emission from neutral or near-neutral Fe irradiated by the hard flaring X-ray source.

Figure 4 shows the undispersed ACIS-S spectra extracted during the first Chandra observation (ObsId 15722). The spectrum corresponding to the first 35 ks of the observation when the count rate was higher ("high-state") is overlaid on that of the remaining ~50 ks segment ("low-state"). The spectrum is slightly harder during the high-state with a hardness ratio \( H/S = 3.17 \) as compared to \( H/S = 2.84 \) in the low-state. The Fe K emission line complex is detected in both the high-state and low-state time segments. Similar to the EPIC pn spectrum, the ACIS-S spectrum extracted during the first 35 ks high-state segment reveals a weak emission feature near 6.4 keV that is undoubtedly fluorescent Fe emission (Figure 4 (bottom)). A similar feature was present in the off-axis zero-order ACIS-S spectrum of RY Tau in 2003 (Audard et al. 2005).

5.2.1. Discrete-temperature Models

We fitted the undispersed spectra with absorbed apec optically thin plasma models to obtain estimates of the absorption column density \( (N_{\text{H}}) \), mean plasma temperature \( (kT) \), metallicity \( (Z) \), X-ray flux \( (F_{\text{x}}) \), and unabsorbed X-ray luminosity \( (L_{\text{x}}) \). Separate fits were obtained for spectra extracted during flare intervals and intervals which excluded obvious flares, as summarized in Table 3. The 1T apec models are overly simplistic in the sense that they only provide a mean temperature and do not give information on how the plasma is distributed versus temperature. The distribution of plasma versus temperature is better assessed with differential EM (DEM) models (Section 5.2.2).

Several conclusions can be reached by examining the fit results in Table 3. Despite the simplicity of the 1T apec model, it gives a surprisingly good fit of the EPIC pn "quiescent" spectrum, with a mean temperature of \( kT = 4.35 \) keV and reduced chi-squared value \( \chi^2_{\nu} = 1.02 \). A fit of the same spectrum with a two-temperature (2T) apec model yields very little further improvement as gauged by the fit statistic (Table 3 Notes). This is a clear indication that the X-ray EM is dominated by hot plasma.

Mean temperatures were higher during flare segments. Very high temperatures occurred during the 25 ks flare segment in the XMM-Newton observation. Fitting the pn spectrum using combined data from both flare peaks gives \( kT_{\text{flare}} = 14.6 \) [11.3–17.9] keV. If spectra extracted for each flare peak are fitted separately, the second peak during which the hard-band count rate reached a maximum yields a slightly higher temperature, but flare temperature uncertainties are large.

The X-ray luminosity is clearly variable. As Table 3 shows, the broad-band luminosity was highest during the high-state in the first ~35 ks of the first Chandra observation (log \( L_{\text{x}} = 31.16 \) erg s⁻¹). The luminosity during the second Chandra exposure (ObsId 17539) and the XMM-Newton observation were lower and comparable to the value log \( L_{\text{x}} = 30.67 \) erg s⁻¹ obtained in 2009 December by Chandra (SAG11). Based on existing observations, the typical luminosity of RY Tau excluding flares is log \( L_{\odot} = 30.65 \) (±0.10) erg s⁻¹. This is at the high end of the range observed.
for cTTS in Taurus (Figure 1 of Telleschi et al. 2007a), as discussed further in Section 6.1.

All 1T apec fits converge to subsolar metallicity with values in the range $Z \approx 0.2 Z_\odot$ (EPIC pn) to $Z \approx 0.4 Z_\odot$ (ACIS-S). Fits in which the abundances of individual elements were allowed to vary show that the low $Z$ values are driven by a low Fe abundance. A low Fe abundance is also obtained using DEM models (Section 5.2.2).

X-ray absorption is best-determined from the EPIC pn spectra which provide better sensitivity at low energies $\lesssim 1$ keV where absorption becomes important. The 1T apec EPIC pn fit of the spectrum with the flare interval excluded (Table 3) gives a best-fit absorption $N_{\text{H}} = 4.3 \times 10^{21}$ cm$^{-2}$. A fit of the pn spectrum during the flare interval gives a nearly identical $N_{\text{H}}$ value (Table 3). This above $N_{\text{H}}$ is in good agreement with estimates based on optically determined $A_V = 2.2 \pm 0.2$ mag (Calvet et al. 2004) using the conversion $N_{\text{H}} = 2.2 \times 10^{21} A_V$ cm$^{-2}$ (Gorenstein 1975), which gives $N_{\text{H}} = 4.8 \pm 0.4 \times 10^{21}$ cm$^{-2}$. By comparison, the conversion $N_{\text{H}} = 1.6 \times 10^{21} A_V$ cm$^{-2}$ of Vuong et al. (2003), gives $N_{\text{H}} = 3.5 \pm 0.3 \times 10^{21}$ cm$^{-2}$, slightly less than inferred from the EPIC pn fits. However, the value inferred for $N_{\text{H}}$ is somewhat sensitive to the spectral model used and more sophisticated DEM models that allow for a range of plasma temperatures give somewhat larger $N_{\text{H}}$ values, as discussed below.

5.2.2. DEM Models

The 1T apec models converge to high plasma temperatures $T \sim 50$ MK ($kT \sim 4$–5 keV) so the X-ray emission is undoubtedly dominated by very hot plasma. However, the presence of low-temperature emission lines in the grating spectra (Section 5.3) indicates that some cool plasma ($T \lesssim 10$ MK) is also present. DEM models allow for plasma distributed over a range of temperatures and thus provide a more realistic picture of the EM distribution than discrete-temperature models.

We have reconstructed the DEM using the variable-abundance XSPEC model x6pvmkl which is based on Chebyshev polynomials.s

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s https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSmodelC6mekl.html
model, as well as a simultaneous fit of the EPIC pn spectrum plus the RGS1 and RGS2 spectra. Flare intervals were excluded in the interest of obtaining a picture of how the plasma is distributed during non-flaring ("quiescent") conditions. Abundances of key elements with detected emission lines in the grating spectra were allowed to vary. Fit results are given in Table 4 and the derived DEM distribution from the best-fit model is shown in Figure 5 (top). There are only minor differences between the DEM fit results obtained fitting the EPIC pn spectrum alone and by fitting the pn and RGS spectra simultaneously. This is a result of the much higher signal-to-noise ratio in the pn spectrum, which dominates the fit.

The DEM is dominated by a prominent peak at \( kT \approx 4\)–5 keV as expected from the 1T apec models. The high-temperature component is well-constrained by the continuum and several highly ionized Fe lines. The DEM drops to a broad minimum near 1 keV (\( T \sim 10\) MK) and then rises slowly toward lower energies. The shape of the DEM below 1 keV is not tightly constrained because it is quite sensitive to absorption \( (N_H)\) which becomes important at low energies and suppresses low-energy emission. Figure 5 (bottom) illustrates how relatively small changes in absorption affect the derived shape of the cool plasma EM distribution. For the best-fit absorption determined by the c6pvmkl model \((N_H = 6 \times 10^{21} \text{cm}^{-2})\), the cool component rises steeply below 0.5 keV toward lower energies. But as \( N_H \) is decreased the cool component contributes less and becomes negligible if \( N_H = 4 \times 10^{21} \text{cm}^{-2}\). In addition to the sensitivity of the derived DEM to \( N_H \), it is worth keeping in mind that the inverse modeling which underlies DEM reconstruction methods suffers from non-uniqueness issues, as has been discussed in previous studies (e.g., Judge & McIntosh 1999). Thus, the DEM reconstruction shown in Figure 5 should not be construed as unique.

The absorption determined from the variable-abundance DEM fit of the pn+RGS “quiescent” spectra is \( N_H = 6.0\)
Table 3
RY Tau Discrete-temperature Model Spectral Fits (0-order)

| Parameter       | Value     |
|-----------------|-----------|
| Telescope       | CXO       |
| ObsId           | 15722     |
| Obs start date  | 22 Oct 2014 |
| Time interval (ks) | 0.0–35.0 |
| Duration (ks)   | 35.0      |
| State           | high-decay |
| Model           | 1T apec   |
| Norm1          | 10^{21} cm^{-2} |
| Norm2          | 10^{-4} cm^{-5} |
| $N_H$          | 5.1 [4.7–6.0] |
| $kT_1$ (keV)   | 6.6 [6.6–9.70] |
| $\chi^2$/dof   | 3.69 [3.45–3.92] |
| $\chi^2$/dof   | 0.4 [0.26–0.52] |
| $\chi^2$/dof   | 138.5/116 |
| $\chi^2$/dof   | 1.19      |
| $F_X$ (10^{-12} erg cm^{-2} s^{-1}) | 4.89 (6.70) |
| $\log L_X$ (erg s^{-1}) | 31.16 |

Notes. Based on XSPEC (vers. 12.8.2) fits of the background-subtracted ACIS-S and EPIC pn spectra binned to a minimum of 20 counts per bin. The tabulated spectral parameters are absorption column density ($N_H$), plasma energy ($kT$), and XSPEC component normalization (norm). Abundances are referenced to Anders & Grevesse (1989). Square brackets enclose 90% confidence intervals. Quantities enclosed in curly braces were held constant during fitting. The total X-ray flux ($F_X$) is the absorbed value in the 0.2–10 keV range, followed in parentheses by unabsorbed value. The total X-ray luminosity $L_X$ is the unabsorbed value in the 0.2–10 keV range and assumes a distance of 134 pc.

Table 4
RY Tau XMM-Newton DEM Model Spectral Fits

| Parameter       | Value     |
|-----------------|-----------|
| Spectra         | pn        |
| ObsId           | 722320101 |
| Time interval   | quiescent |
| Model           | cgsveNhk  |
| Norm1          | 10^{21} cm^{-2} |
| Norm2          | 10^{-4} cm^{-5} |
| $N_H$          | 6.0 [5.0–6.8] |
| $kT_1$ (keV)   | 4.1 [3.3–5.8] |
| $\chi^2$/dof   | 0.46 [0.22–0.87] |
| $\chi^2$/dof   | 453.6/469 |
| $\chi^2$/dof   | 0.97      |
| $F_X$ (10^{-12} erg cm^{-2} s^{-1}) | 1.04 (2.73) |
| $\log L_X$ (erg s^{-1}) | 30.77 |

Notes. Based on XSPEC (vers. 12.8.2) fits of the background-subtracted EPIC pn and RGS1&2 spectra using a variable-abundance cgsveNhk model. Abundances are referenced to Anders & Grevesse (1989). Square brackets enclose 90% confidence intervals. The total X-ray flux ($F_X$) is the absorbed value in the 0.2–10 keV range, followed in parentheses by unabsorbed value. The total X-ray luminosity $L_X$ is the unabsorbed value in the 0.2–10 keV range and assumes a distance of 134 pc.

5.3. X-Ray Grating Spectra
5.3.1. XMM-Newton RGS

The first-order RGS1 and RGS2 spectra for the full usable exposure are shown in Figure 6. Emission lines and line photon fluxes are listed in Table 5, along with upper limits for [5.2–7.1; 90% conf.] $\times 10^{21}$ cm^{-2}, nearly identical to that obtained from 1T apec fits of the ACIS-S low-state spectrum for ObsId 15722 (Table 3). It is also consistent with the value $N_H = 5.5 [4.7–6.8] \times 10^{21}$ cm^{-2} obtained by Chandra ACIS-S in 2009 (SAG11) and in the 2003 Chandra off-axis exposure (Audard et al. 2005). The above absorption determinations are consistent with the value expected based on $A_V = 2.2 \pm 0.2$ mag using the Gorenstein (1975) conversion which, as noted in Section 5.2.1, gives $N_H \approx 4.8 \pm 0.4 \times 10^{21}$ cm^{-2}. But they are somewhat higher than the value $N_H = 3.5 \pm 0.3 \times 10^{21}$ cm^{-2} obtained using the Vuong et al. (2003) conversion. Thus, some excess X-ray absorption above that expected from $A_V$ may be present.

The DEM model fit converges to a subsolar Fe abundance $Fe = 0.31 [0.23–0.38]$; 90% confidence interval $\times$ solar. The other elemental abundances are not as tightly constrained but O is also subsolar and the abundance ratio Ne/Fe $\approx 2.5–2.9$ is similar to values reported for other TTS in Taurus including the prototype T Tau (Güdel et al. 2007a; Telleschi et al. 2007b). The above abundances are relative to the solar reference values of Anders & Grevesse (1989).
important non-detections. Line fluxes were measured by fitting lightly binned spectra using a Gaussian line profile fixed at the instrumental width and a power-law model of the adjacent continuum. For faint lines the Gaussian centroid was fixed at the line reference energy but for brighter lines the centroid was allowed to vary. Since the background is high and the line signal-to-noise ratios are low, we analyzed total RGS1 and RGS2 spectra (source + background) as recommended by XMM-Newton RGS analysis guidelines.9

Visible lines at higher energies above 1 keV are Ne X at 1.022 keV (12.134 Å) and Mg XII at 1.47 keV (8.42 Å). The Si XIII triplet near 1.86 keV may also be present but is more clearly detected in the Chandra MEG spectrum (Figure 7). At low energies below 1 keV background begins to dominate and line identifications become more uncertain. Fe XVII is present and the O VIII line at 0.654 keV (18.97 Å) is also visible in RGS2 but is weak or absent in RGS1. The Ne IX triplet is not detected by RGS2 and there is no RGS1 coverage of Ne IX. There is a noticeable feature in RGS1 at $E = 0.577 \pm 0.002$ (1σ) keV which is slightly higher than the reference energy of the O VIII resonance line ($E_{\text{ref}} = 0.574$ keV). RGS2 lacks coverage at this energy. There is a Ca XVI transition at $E_{\text{ref}} = 0.577$ keV but RGS1 simulations do not reproduce the Ca line. If the feature is interpreted as O VIII then the rather large 3 eV blueshift is not readily explained as a calibration offset or a Doppler shift such as might arise if O VIII formed in the blueshifted jet. The latter interpretation would require much higher jet speeds than have been obtained from optical measurements (Section 6.4). The identification of this feature as O VIII is thus questionable and inspection of the RGS1 background spectrum raises suspicions that it is noise-related.

9 http://xmm.esac.esa.int/sas/current/documentation/threads/rgs_thread.shtml

10 Details on RGS wavelength calibration can be found at http://xmm2.esac.esa.int/docs/documents/CAL-TN-0030.pdf.
### Table 5

| Ion        | \(\lambda_{\text{ref}}\) (Å) | \(E_{\text{ref}}\) (keV) | \(E_{\text{obs}}\) (keV) | Line Flux (MEG) \(\times 10^{-6}\) ph cm\(^{-2}\) s\(^{-1}\) | Line Flux (RGS) \(\times 10^{-6}\) ph cm\(^{-2}\) s\(^{-1}\) | \(\log T_{e,\text{max}}\) (K) |
|------------|-------------------------------|--------------------------|----------------------------|-------------------------------------------------|---------------------------------|------------------------|
| Fe xxv\(^{bc}\) | 1.850                         | 6.702                    | 6.664                      | 7.86 ± 4.52                                    | ...                             | 7.8                    |
| Ca xix     | 3.177                         | 3.903                    | 3.902                      | 3.76 ± 1.56                                    | ...                             | 7.5                    |
| Si xiv Ly\(\alpha\) | 6.182                      | 2.006                    | 2.006                      | 8.34 ± 1.27                                    | ...                             | 7.2                    |
| Si xiv (r) | 6.648                         | 1.865                    | 1.865                      | 4.43 ± 1.02                                    | ...                             | 7.0                    |
| Si xiv (i) | 6.688                         | 1.854                    | [1.854]                    | 1.81 ± 0.80                                    | ...                             | 7.0                    |
| Si xiv (f) | 6.740                         | 1.840                    | [1.840]                    | 3.55 ± 0.91                                    | ...                             | 7.0                    |
| Mg xii     | 7.106                         | 1.745                    | 1.744                      | 1.73 ± 0.73                                    | ...                             | 7.0                    |
| Fe xxiv    | 7.457                         | 1.663                    | 1.663                      | 1.34 ± 0.65                                    | ...                             | 7.3                    |
| Mg xii Ly\(\alpha\) | 8.421                      | 1.472                    | 1.472                      | 5.54 ± 0.97                                    | 5.66 ± 3.51                      | 7.0                    |
| Mg xii (r) | 9.169                         | 1.352                    | 1.352                      | 4.02 ± 1.57\(^d\)                              | \(\leq 3.36\)                     | 6.8                    |
| Mg xii (i) | 9.231                         | 1.343                    | [1.343]                    | \(< 1.14\)\(^d\)                              | ...                             | 6.8                    |
| Mg xii (f) | 9.314                         | 1.331                    | [1.331]                    | \(< 1.43\)\(^d\)                              | ...                             | 6.8                    |
| Fe xxix\(^b\) | 10.021                      | 1.237                    | 1.237                      | 1.95 ± 0.91                                    | ...                             | 7.1                    |
| Ne x Ly\(\beta\) | 10.239                      | 1.211                    | [1.211]                    | \(< 0.60\)                                     | ...                             | 6.8                    |
| Fe xxiv\(^b\) | 10.619                      | 1.168                    | 1.167\(^g\)                | 3.57 ± 1.12                                    | ...                             | 7.3                    |
| Fe xcv     | 11.176                        | 1.109                    | 1.109                      | 2.05 ± 0.97                                    | ...                             | 7.3                    |
| Fe xcm     | 11.736                        | 1.056                    | 1.056                      | 2.50 ± 1.24                                    | ...                             | 7.2                    |
| Ne x Ly\(\alpha\) | 12.134                      | 1.022                    | 1.021                      | 3.99 ± 1.73                                    | 3.65 ± 1.72                       | 6.8                    |
| Ne x Ly\(\beta\) | 13.447                      | 0.922                    | [0.922]                    | \(< 3.65\)\(^f\)                              | \(< 2.44\)                      | 6.6                    |
| Fe xv     | 15.014                        | 0.826                    | [0.826]                    | \(< 2.19\)                                     | 1.78 ± 1.46\(^h\)               | 6.8                    |
| O viii Ly\(\beta\) | 16.006                      | 0.775                    | [0.775]                    | ...                                            | \(< 3.05\)                      | 6.5                    |
| Fe xv\(^b\) | 16.780                        | 0.739                    | 0.736                      | ...                                            | 1.59 ± 1.53\(^f\)               | 6.8                    |
| O viii Ly\(\alpha\) | 18.969                      | 0.654                    | 0.655                      | 2.44 ± 2.33\(^i\)                              | ...                             | 6.5                    |
| O viii (r) | 21.602                        | 0.574                    | [0.574]                    | ...                                            | \(< 3.09\)                      | 6.3                    |

**Notes.**

\(^{a}\)Observed line energies and fluxes are from continuum-subtracted first-order HETG/MEG (ObsId 15722) and RGS (Obs 722320101) full-exposure spectra (flare +quiescent), unless otherwise noted. Tabulated quantities are: ion name (Ion) where \(r\), \(i\), \(f\) denote resonance, intercombination, and forbidden lines of He-like triplets; reference wavelength \(\lambda_{\text{ref}}\) and energy \(E_{\text{ref}}\) of transition from AtomDB version 3.0.2 (www.atomdb.org); measured line-centroid energy \(E_{\text{obs}}\) where square brackets mean the value was held fixed during fitting; observed (absorbed) continuum-subtracted line flux (Line Flux) with 1\(\sigma\) uncertainties (upper limits are 1\(\sigma\)); and maximum line emissivity electron temperature \(T_{e,\text{max}}\). An ellipsis means no reliable flux measurement was obtained.

\(^{b}\)Possible blend.

\(^{c}\)The observed line flux and centroid energy are from the first-order HEG spectrum. There are four closely spaced Fe xxv lines in the range 6.637–6.702 keV (Figure 7). Their emissivity-weighted average energy is 6.682 keV. The flux was measured with the Gaussian line width fixed at the instrumental value. The observed feature is broadened, indicating that multiple lines contribute.

\(^{d}\)MEG fluxes and upper limits for Mg xii are from high-state spectrum. Undetected in low-state.

\(^{e}\)There is also weak emission from Fe xviii/xix at 1.196 keV in the MEG spectrum.

\(^{f}\)Low-significance feature; possible line detection.

\(^{g}\)Faint Ne x emission may be present in MEG. See text.

\(^{h}\)Low-significance RGS features are also present in the Fe xcv/xvi complex at 0.727–0.739 keV.

\(^{i}\)The quoted O viii line flux is from a feature visible in RGS2. Not confirmed in RGS1 or MEG.

\(^{j}\)There is a feature visible at 0.577 ± 0.002 (1\(\sigma\)) keV in RGS1 with observed flux 2.17 ± 2.06 \(\times 10^{-6}\) ph cm\(^{-2}\) s\(^{-1}\). There is no corresponding RGS2 coverage at this energy. Because of the slight energy offset this feature cannot be conclusively identified as O viii.

### 5.3.2. Chandra HETG

The first-order MEG spectrum from the longer first observation (ObsId 15722) is shown in Figure 7 along with a portion of the HEG spectrum in the vicinity of the high-temperature Fe K\(\alpha\) line complex. Several emission lines are detected (Table 5) superimposed on a hot continuum. The emission lines span a broad range of temperature as judged from maximum line emissivity temperatures of \(\sim 6\) MK (Ne x) up to \(\sim 63\) MK (Fe xxv; visible in HEG). There are no high-confidence HETG line detections at energies below 1 keV but weak Ne x emission may be present near 0.922 keV (13.447 Å) as discussed further in Section 5.4. The absence of strong line detections below 1 keV is attributable to the rapid falloff in ACIS-S/HETG effective area at low energies and the effects of source absorption. We also note that potentially useful Ly\(\beta\) lines from O and Ne are not detected so estimates of \(N_{\text{H}}\) using Ly\(\alpha\)/Ly\(\beta\) flux ratios are precluded.

The excellent energy resolution and calibration of HETG permit a rigorous comparison of observed line-centroid energies with their reference (rest-frame) values and checks for line-broadening. Best-fit first-order MEG line-centroid energies (Table 5) show no significant offsets from the reference energies given in ATOMDB v3.0.2.\(^{11}\) Gaussian fits of the brightest lines yield centroid energies that differ by at most \(\pm 1\) eV from reference energies, well within MEG calibration accuracy.\(^{12}\) Measured line-widths of the brightest lines (Si xiv, Si xiv, Mg xii, Ne x) do not exceed instrumental values. Thus, no evidence for significant centroid shifts or excess line-broadening is found for those lines bright enough to confidently measure line properties.

\(^{11}\)www.atomdb.org

\(^{12}\)http://cxc.harvard.edu/proposer/POG/html/
The high plasma temperatures inferred from zero-order ACIS-S fits are confirmed by continuum fits of the MEG spectrum using intervals with no discernible line emission, as determined by visual inspection and the ATOMDB line list. Fits of the MEG spectrum obtained during the first exposure (ObsId 15722) using an absorbed 1T bremsstrahlung model give $kT = 8.0^{+4.3}_{-4.3}$ keV for the high-state interval and $kT = 4.4^{+8.3}_{-1.9}$ keV for the subsequent low-state, where the errors are 1σ. No useful constraint on the upper limit of $kT$ was obtained for the high-state spectrum. Because of the limited number of channels fitted after removing line intervals, no significant improvement was obtained using a 2T bremsstrahlung model. The above values are similar to those obtained from ACIS-S fits using 1T apec models (Table 3).

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The first-order MEG spectrum from the second shorter observation (ObsId 17539) contains only 495 counts as compared to 3796 MEG counts in the first observation. The lower number of counts in the second observation is due to the shorter exposure time and the lower count rate (Figure 2). Since the spectrum was evolving between the first and second observations we have chosen not to coadd the two MEG spectra. Only the brightest emission lines were detected in the second observation (i.e., Si XIV Lyα, Si XIII, Mg XII Lyα). The fluxes of these brightest lines are similar in the two observations and their respective 1σ confidence flux ranges overlap, albeit with larger flux uncertainties in the second observation due to fewer counts. For the brightest line in the spectrum, Si XIV Lyα, the flux from the second observation is $F_{\text{Si XIV}} = 8.26 \pm 3.37 \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$, in good agreement with the first observation (Table 5).

### 5.4. He-like Triplets

Line emission from He-like triplets is summarized in Table 6. Line flux ratios of the resonance ($r$), intercombination ($i$), and forbidden ($f$) lines of He-like triplets are important plasma diagnostics (Porquet et al. 2001). One or more of the triplet lines of Si XIII and Mg XI is visible in the MEG first-order spectrum. Weak emission is also present in MEG at the reference energies of the Ne IX $r$ and $i$ lines, as discussed further below. The O VII triplet was not detected by MEG and the identification of the feature in RGS1 offset by 3 eV from the O VII reference energy is uncertain.

In He-like triplets, the line flux ratio $R = f/i$ is sensitive to both electron density $n_e$ and the UV radiation field (Gabriel & Jordan 1969). If $\phi$ is the photoexcitation rate from the $^3S_1$ level
Table 6

| Si xii | Mg xi |
|--------|-------|
| Grating | HETG (MEG) | HETG (MEG) |
| Time interval | total | high-state |
| Flux($i$) | $4.43 \pm 1.02$ | $4.02 \pm 1.59$ |
| Flux($f$) | $1.81 \pm 0.80$ | $<1.14$ |
| flux($i$) | $3.55 \pm 0.91$ | $<1.43$ |
| $G$ | $1.21^{+0.36}_{-0.54}$ | $<0.64$ |
| $R$ | $1.96^{+0.46}_{-0.95}$ | ... |
| $R_{0}$ | 2.3 | 2.7 |
| log $T_{e,\text{max}}$ (K) | 7.0 | 6.8 |
| log $T_{e}$ (K) | $6.6^{+0.4}_{-0.7}$ | $>6.9$ |
| log $n_{e}$ (cm$^{-3}$) | $13.0^{+0.9}_{-1.0}$ | ... |

Notes

1. Line fluxes are from $\text{Chandra}$ MEG 1st order spectra (+1 and $-1$ orders combined) for ObsId 15722. The Mg xi flux is from the high-state spectrum obtained during the first 35 ks of the observation. The flux ratios are defined as $G = (f + i)/r$ and $R = f/r$. Uncertainties are $\pm 1$σ. Flux upper limits are $1$σ. Limiting values for $G$ and $R$ use $1$σ flux upper limits. $R_{0}$ is the theoretical low-density limit at maximum emissivity temperature $T_{e,\text{max}}$ (Porquet & Dubau 2000; Porquet et al. 2001). The derived values of $T_{e}$ and $n_{e}$ assume negligible photoexcitation.

2. Line photon flux in units of $10^{-6}$ ph cm$^{-2}$ s$^{-1}$.

3. No useful constraint obtained.

4. RY Tau is one of the most massive and rapidly accreting CTTS in Taurus. It is remarkably similar to the prototype T Tau N which dominates the X-ray and optical emission of the multiple T Tau system (Güdel et al. 2007a). RY Tau and T Tau N have similar masses, accretion rates, $N_{H}$, and Ne/Fe abundance ratios (Calvet et al. 2004; Güdel et al. 2007a). Both stars have X-ray spectra consisting of an admixture of very hot and very cool plasma with both components exhibiting slow light-curve variability (Figure 2 of Güdel et al. 2007a). The X-ray luminosity of T Tau is $\log L_{x}(0.3-10\text{ keV}) = 31.18$ erg s$^{-1}$ ($d = 140$ kpc), comparable to or slightly greater than that of RY Tau. However, there are a few notable differences. T Tau is a multiple system consisting of at least three closely spaced objects (T Tau N, T Tau Sα,b) whereas binarity in RY Tau is suspected but has so far not been proven. In addition, no well-collimated large-scale optical jet such as that observed for RY Tau has yet been reported for the T Tau system.

6. DISCUSSION

6.1. RY Tau in Context: the Taurus CTTS Population

The X-ray spectrum of RY Tau reveals spectral lines from a broad range of plasma temperature superimposed on a hot continuum. The X-ray spectrum and light curves are highly variable, including short-duration ($\sim$ hours) high-temperature flares signaling strong magnetic activity superimposed on slower light-curve modulation spanning at least $\sim$ one day. The DEM is dominated by very hot plasma with a peak near $kT \approx 4-5$ keV ($T \approx 50$ MK) and a weaker contribution from cool plasma below 1 keV ($T \lesssim 10$ MK). Higher temperatures $kT \approx 8$ keV ($T \sim 90$ MK) are inferred during flares. The unabsorbed X-ray luminosity is variable with a typical value $\log L_{x} = 30.65$ ($\pm 0.1$) erg s$^{-1}$ outside of flares. The absorption column density $N_{H}$ is comparable to or perhaps slightly greater than that predicted from $A_{V}$. The Fe abundance is significantly subsonar. Undispersed CCD spectra show a faint emission line near 6.4 keV from fluorescent Fe arising in cold material near the star irradiated by the hard X-ray source. No significant line-centroid shifts or line-broadening were detected for the brightest lines in $\text{Chandra}$ MEG spectra. The $R$ ratio computed for the Si xii He-like triplet is consistent with that expected in the low-density limit. The Mg xi triplet resonance line is only visible in the $\text{Chandra}$ MEG spectrum during the high-state when a high plasma temperature was inferred and is thus evidently associated with hot plasma, not shocks. Low-temperature emission lines are generally faint or absent as a result of absorption and RGS noise, although Fe xviii ($T_{e,\text{max}} \sim 6$ MK) and O vii Ly$\alpha$ ($T_{e,\text{max}} \sim 3$ MK) are visible in the RGS spectra.

weak Ne ix emission in MEG may contain contributions from Fe xix and Fe xxi and in any case the emission is too faint to obtain reliable line flux measurements. Thus, we only give an upper limit for Ne ix in Table 5.

5.5. Summary of Spectral Analysis
determined from the parametric estimation (EM) method and $A = 1.98 \pm 0.20$ and $B = 30.24 \pm 0.06$ from the bisector method. We take $L_{\alpha}$ as the known quantity derived from our X-ray spectral fits and adopt $\log L_{\alpha} = 30.65 \pm 0.13 \text{ erg s}^{-1} \text{ (d = 134 pc)}$ as a typical value for RY Tau outside of flares, where the uncertainties reflect only the range of low-state ("quiescent") $L_{\alpha}$ values (Tables 3 and 4). Adjusting this value upward to $\log L_{\alpha} = 30.69 \pm 0.13 \text{ erg s}^{-1}$ at the distance of 140 pc used in the XEST study gives $M_\ast = 2.1 \times (1.8-2.7) M_\odot$ from the EM-method relation and $M_\ast = 1.7 \times (1.5-1.9) M_\odot$ from the bisector method, where the range in parentheses accounts only for the uncertainties in XEST regression fit parameters. These mass estimates are in very good agreement with previously published estimates for RY Tau (Table 1). Thus, even though $L_{\alpha}$ for RY Tau is among the highest of cTTS studied in Taurus (Figure 1 of Telleschi et al. 2007a), it is consistent with expectations given that its mass is also high.

XEST regression fit results for the EM and bisector methods are similar for the low-state $L_{\alpha}$ versus $L_{\alpha}$ correlation for cTTS in Taurus, which is $\log L_{\alpha} = C \cdot \log(L_{\alpha}/L_{\odot}) + D$ (erg s$^{-1}$) where $C = 1.16 \pm 0.09$ and $D = 29.83 \pm 0.06$. Inserting $\log L_{\alpha} = 30.69$ for RY Tau yields $L_{\alpha} = 5.5 \times (4.4-7.2)L_{\odot}$. This regression fit prediction is a bit lower than previously reported $L_{\alpha}$ values (Table 1) but the upper limit $L_{\alpha} = 7.2L_{\odot}$ is nearly equal to the value 7.6$L_{\odot}$ determined by Kenyon & Hartmann (1995). Given that the spectral type of RY Tau is somewhat uncertain (and hence its bolometric correction as well) and that the low-state ("quiescent") $L_{\alpha}$ value is also uncertain by $\pm 0.1$ dex, the above difference is not significant. We conclude that published values of $M_\ast$ and $L_{\alpha}$ for RY Tau are in acceptable agreement with predictions based on XEST correlations for cTTS in Taurus.

6.2. The 6.4 keV Fluorescent Fe Line

The 6.4 keV fluorescent Fe emission line is visible in both the EPIC pn and ACIS-S flare or high-state spectra, but is not present in the quiescent or low-state spectra (Figures 3 and 4). Thus, the fluorescent line is excited by hard X-rays produced in flares or high emission states irradiating cold nearby material. Photon energies $E > 7.11$ keV are needed to eject a K-shell electron which is followed by a downward transition (e.g., from the L-shell) to produce the 6.4 keV line. The association of fluorescent Fe emission with flares in young stars and protostars has been seen before, but in unusual cases such as the protostar NGC 2071 IRS1 the 6.4 keV feature is present even in the absence of discernible flares (Skinner et al. 2007, 2009).

Measurements of the continuum-subtracted 6.4 keV line flux in the ACIS-S flare-segment spectrum (ObsId 15722) give $F_{6.4}=7.5 \times (1.5-13) \text{ erg cm}^{-2} \text{ s}^{-1}$, where the uncertainty is 90% confidence. The underlying continuum flux density is $F_{\text{cont}}=4.4 \times (0.4-13) \text{ erg cm}^{-2} \text{ s}^{-1}$ keV$^{-1}$. The above values give a line equivalent width (EW) $EW = 0.17 \pm 0.05$ keV. For comparison, the line flux from the 2003 off-axis ACIS-S spectrum was $F_{6.4,0}=4.4 \times (2.0-13) \text{ erg cm}^{-2} \text{ s}^{-1}$ (Audard et al. 2005). In our 2013 XMM-Newton observation the EPIC pn 6.4 keV line is narrow and weak and the line flux is quite uncertain but line flux estimates are comparable to that given above for the 2003 Chandra off-axis observation.

The fluorescent line EW is related to the column density of cold fluorescent material in the optically thin slab approximation by $EW \approx 2.3 N_{24} [\text{keV}]$ (Kallman 1995). For $N_{24}$, is the column density of the cold matter in units of $10^{24}$ cm$^{-2}$. Using the value $EW = 0.17 \pm 0.05$ keV from the 2014 ACIS-S flare spectrum gives $N_{24} = 7.4 \pm 2.2 \times 10^{22}$ cm$^{-2}$. This value is an order of magnitude greater than inferred from the spectral fits (Table 3), so dense cold target material located near the star but off the line of sight is required. Accreting gas or disk gas are two likely possibilities for the irradiated material.

6.3. Slow Variability

The slow decline followed by a slow rise in the Chandra light curves of the first observation is present in very-soft, medium, and hard energy bands (Figure 2). This is a strong clue that the very-soft-, medium-, and hard-band emission have a common origin (Section 6.3). Similar slow X-ray light-curve variability is present in the shorter second Chandra observation (Figure 2) and was previously seen in the 2009 Chandra observation (Figure 2 of SAG11) and the 2003 Chandra off-axis exposure. Furthermore, the EPIC pn light curve in the 1–2 keV band on 2013 August 21–22 is rising slowly but no slow variability is obvious in the pn hard-band where rapid flares are most conspicuous (Figure 1). Taken together, these results suggest that RY Tau is in a persistent state of slow X-ray modulation accompanied by intermittent rapid flares.

In order to determine how the X-ray parameters changed with time during the slow decay and rise in the new Chandra observation (ObsId 15722), we extracted ACIS-S spectra from five non-overlapping time intervals that span the 85 ks observation. Each spectrum was fitted with an absorbed isothermal 1T apec model with metallicity fixed at $Z = 0.4 Z_\odot$. The variation of the mean plasma temperature $kT$ and absorbed broad-band X-ray flux $F_x$ versus time are shown in Figure 8, along with the hard-band ACIS-S light curve.

It is apparent from Figure 8 that $kT$ and $F_x$ declined steadily until the hard-band count rate reached a minimum at elapsed time $t \approx 40–50$ ks and then they increased. The EM, as gauged by the XSPEC model norm, mimics the time behavior of $kT$ and $F_x$. An exponential fit of the the $kT$ versus time decay profile (Figure 8 (top)) gives an e-folding time of 52.6 ks (14.6 hr).

What is intriguing about the time evolution is that even though $kT$ clearly increased near the end of the observation after the hard-band count rate reached minimum, there is no clear signature of an impulsive flare in the hard-band light curve (Figure 2) that might have triggered the reheating. Although a slowly developing flare could be responsible for the gradual brightening after the Chandra light curve reached minimum, the absence of any discernible hard-band flare in combination with the similar slowly changing count rates in different energy bands is more suggestive of variability associated with one or more surface features rotating across the line of sight. The conclusion that the slow light-curve variability may be linked to surface structures rotating across the line of sight is tentative since no definite stable period of order $\sim$days that could arise from stellar rotation has yet been found in X-rays or optical. However, Holtzman et al. (1986) have presented compelling arguments for surface structures ("spots") on RY Tau based on their analysis of optical photometric and spectroscopic variability.
are aligned we obtain the stellar parameters. Estimates of the stellar radius range from 1.3 mm data – 2.9 – 0.4 \( R_\odot \) (Calvet et al. 2004) to 5.0 ± 0.3 \( R_\odot \) (Takami et al. 2013). Petrov et al. (1999) obtained a projected rotational velocity \( v\sin i = 52 \pm 2 \text{ km s}^{-1} \). The disk inclination is quite uncertain with published estimates ranging from \( i_{\text{disk}} = 25^\circ \pm 3^\circ \) (Akenson et al. 2005) to \( i_{\text{disk}} = 66^\circ \pm 2^\circ \) (1.3 mm data) or 71° ± 6° (2.8 mm data), the last two being derived from CARMA mm interferometry (Isella et al. 2010). Based on the above we adopt the representative values \( R_\ast = 4 \pm 1 \text{ \( R_\odot \), } v\sin i = 52 \pm 2 \text{ km s}^{-1}, \text{ and } i_{\text{disk}} = 48^\circ \pm 24^\circ \). Under the additional assumption that the stellar and disk rotation axes are aligned we obtain \( P_{\text{rot}} = 2.9 \text{ (1.2–4.8 days when the range in parentheses reflects the spread in adopted stellar parameters. We emphasize that the above is just an estimate and not a substitute for an observational period determination.}

We are not aware of any reports of optical periods of \(<5 \text{ days for RY Tau. A slight peak of 5.6 days was noted in a periodogram by Herbst et al. (1987) but after more detailed analysis no significant power near 5.6 days was seen. Later attempts to recover the 5.6 day signal also gave negative results (Herbst & Kores 1988; Bouvier et al. 1993). A low-significance peak of 7.5 days was claimed by Zajtseva (2010) in optical photometry obtained during 1996 but to our knowledge this period has not been confirmed. There have been reports of periods in the range \( \sim 20–24 \text{ days but these are too long to be due to rotation as was noted by Bouvier et al. (1993).}

On a rapidly rotating accreting young star like RY Tau surface structures could originate in coronal active regions or at accretion footpoints, giving rise to X-ray modulation. Periodic X-ray modulation was found in 23 young stars in the Chandra Orion COUP sample (Flaccomio et al. 2005). In most cases the X-ray period was close to the known optical period (\( P_{\text{opt}} \sim 2–14 \text{ days} \) but in some cases the X-ray period was about half the optical period. Compact sizes less than (or much less than) \( R_\ast \) were inferred for the X-ray structures responsible for the modulation. In addition, possible periodic X-ray modulation in the eruptive young star V1647 Ori was attributed to surface structures associated with accretion footpoints (Hamaguchi et al. 2012).

Since the slow Chandra light-curve variability is present in very soft and hard energy bands, it is unlikely that the surface structures thought to underlie the variability are accretion footpoints. The predicted accretion shock temperature for RY Tau is \( T_s \sim 3 \text{ MK} \) (Section 6.4) and such cool plasma would have little if any effect on the hard-band (2–8 keV) light curve. Identification of the presumed surface structures with one or more active regions spanning a range of temperature (and density) seems to be in better accord with the light-curve variations. Any role that the hypothesized (but as yet unseen) companion might play in the X-ray variability cannot be reliably assessed without specific information regarding the companion type and its orbit.

The volume \( V \) of the X-ray emitting region can be estimated from the volume EM, \( \text{EM} = n_e^2 V \), where \( n_e \) is the average electron density in the emitting region. A numerical value of EM is obtained from the XSPEC norm in spectral fits via the relation (Table 3 notes) \( \text{EM} = 2.15 \times 10^{56} \text{ norm (cm}^{-3} \) ). In non-flaring states the IT \( \text{apec} \) fits give norm \( \sim (1–2.5) \times 10^{-3} \text{ cm}^{-3} \) (Table 3) and as a representative value we adopt norm \( \sim 1.5 \times 10^{-3} \text{ cm}^{-3} \). This yields \( \text{EM} = 3.2 \times 10^{53} \text{ cm}^{-3} = n_e^2 V \) which would include any excess X-ray EM from active regions as well as a basal contribution from the ambient corona. As such, it is only an upper limit on any active region contribution. For a stellar radius \( R_\ast = 2.9 \text{ \( R_\odot \) (Calvet et al. 2004) the ratio of emitting region volume to stellar volume is } V/V_\ast \approx 0.1/\text{em}^2 \text{ m} \), where \( n_e,10 \) is the average density in units of \( 10^{10} \text{ cm}^{-3} \).

Coronal densities in late-type stars determined from O vii and Ne ix triplet line ratios are typically in the range \( n_e \sim 10^{10}–10^{12} \text{ cm}^{-3} \) (Ness et al. 2004). Active region densities on the Sun obtained from spatially resolved Hinode observations are in the range \( n_e \sim 10^{6–10} \text{ cm}^{-3} \) (Pradep et al. 2012), being at the high end of this range in the active region core. For an assumed average \( n_e \sim 10^{10} \text{ cm}^{-3} \) the relation obtained above for RY Tau gives \( V \approx 0.1 V_\ast \) and a characteristic emitting region radius \( R = V/V_\ast \approx 0.75 R_\ast \). For a surface filling factor \( f \) the relation \( R = \sqrt{f} R_\ast \) yields \( f = 0.56 \). Higher densities are certainly possible as referenced above and are compatible with the Si xi triplet line ratios (Table 6), so a small emitting volume \( V < V_\ast \) seems assured and the filling factor need not be large.

6.4. Cool Plasma: Shocks or Corona?

The presence of the O viii Ly\( \alpha \) emission line in the RGS2 spectrum supports the conclusion from DEM fits (Figure 5) that some cool plasma is present. The O viii line has a maximum emissivity temperature \( T_{e,max} \approx 3 \text{ MK} \) but the emissivity is still substantial up to higher temperatures of \( >5–6 \text{ MK} \). Cool plasma at \( T \lesssim 3 \text{ MK} \) could potentially arise in shocks, and a cool coronal component at \( T \sim 3–6 \text{ MK} \) could also produce the O viii line.

**Shocked Jet.** Plasma temperatures of \( \sim 3 \text{ MK} \) are difficult to achieve for a shocked jet in RY Tau based on current jet speed estimates. As discussed in SAG11, the maximum shock temperature for a shock-heated jet is \( T_s = 0.15 v_\ast^2 \text{ Mkm} \), where \( v_\ast \) is the jet speed in units of \( 100 \text{ km s}^{-1} \) (Raga et al. 2001).
et al. 2002). The optically derived jet speed for RY Tau is \( v_{\text{jet}} \approx 165 \text{ km s}^{-1} \) which leads to a maximum predicted shock temperature \( T_s \approx 0.4 \text{ MK} \) \((kT_s \approx 0.035 \text{ keV})\). At this temperature, almost all of the X-ray emission would emerge at energies below 0.2 keV where XMM-Newton or Chandra have very little sensitivity. Unless the jet speed is higher than estimated from optical observations or other jet-heating mechanisms besides shocks are at work, a jet origin for the cool X-ray plasma is difficult to justify.

**Accretion Shock.** The case for producing cool \((T \sim 3 \text{ MK})\) X-ray plasma and the \( \text{O} \text{ VIII} \) line by an accretion shock is more favorable. The post-shock temperature for a strong accretion shock is

\[
T_s = 2.27 \times 10^5 \mu \left( \frac{v_i}{100 \text{ km s}^{-1}} \right)^2 \text{K},
\]

where \( \mu \) is the mean mass (amu) per particle in the accreting gas and \( v_i \) is the free-fall speed at the shock front (Calvet & Gullbring 1998). To estimate \( v_i \), we adopt the stellar parameters of Calvet et al. (2004), namely \( M_* = 2.0 M_\odot \), \( R_* = 2.9 R_\odot \). The accretion rate is somewhat uncertain but the various models considered by Schegerer et al. (2008) are compatible with rates of \( \dot{M}_{\text{acc}} \approx \left(2.5 \text{--} 9.1\right) \times 10^{-8} \dot{M}_\odot \text{ yr}^{-1} \). We adopt a value in the middle of this range \( \dot{M}_{\text{acc}} = 5 \times 10^{-8} \dot{M}_\odot \text{ yr}^{-1} \). In the absence of a magnetic field measurement we assume a typical cTTS value \( B_s \approx 2000 \text{ G} \) (Johns-Krull 2007). Using Equation (1) of Königl (1991) we obtain an inner disk truncation radius from which the infalling material is assumed to originate of \( r_{\text{in}} \approx 7.15 R_\odot \), assuming spherical accretion and H-ionized solar abundance plasma \((\mu = 0.6)\). Equation (1) of Calvet & Gullbring (1998) then gives \( v_s \approx 479 \text{ km s}^{-1} \) corresponding to a post-shock temperature \( T_s \approx 3.1 \text{ MK} \) \((kT_s \approx 0.27 \text{ keV})\). The value of \( T_s \) is only weakly dependent on the poorly known values \( B_s \) and \( \dot{M}_{\text{acc}} \).

For our adopted stellar parameters the post-shock electron density for a strong shock is (Equation (3) of Telleschi et al. 2007b) \( n_e \approx 5.7 \times 10^{13} \text{ cm}^{-3} \), where \( \dot{M}_{\text{acc}} \) is in units of \( 10^{-8} \dot{M}_\odot \text{ yr}^{-1} \) and \( f \) is the surface filling factor which is not well-known but is usually taken to be in the range \( f = 0.001 \text{--} 0.1 \). For \( n_{\text{acc}} \approx 5 \) and \( f \leq 0.1 \) the lower limit is \( n_e \approx 2.8 \times 10^{13} \text{ cm}^{-3} \). This value is higher than typical coronal densities \( n_e \approx 10^{10} \text{--} 10^{11} \text{ cm}^{-3} \) for active stars based on \( \text{O VIII} \) triplet \( R \) ratios (Ness et al. 2004). The total accretion luminosity is (Calvet & Gullbring 1998) \( L_{\text{acc}} \approx 3.6 \times 10^{33} \text{ erg s}^{-1} \) \((= 0.94 \text{ L}_\odot)\). For comparison, we note that the observed (absorbed) flux of the \( \text{O VIII} \text{ Ly} \alpha \) line gives \( L_{\text{O VIII} \text{ Ly} \alpha} \approx 4.8 \times 10^{32} \text{ erg s}^{-1} \) with an uncertainty of about a factor of two. The intrinsic (unabsorbed) luminosity depends sensitively on \( N_{\text{H}} \) toward the line-forming region and would be larger.

We have fitted the RGS2 spectrum (flares excluded) using a 2T \( v\text{apex} \) optically thin plasma model to estimate the temperature range needed to reproduce the \( \text{O VIII} \text{ Ly} \alpha \) line. Absorption was restricted to the range \((4 \text{--} 6) \times 10^{21} \text{ cm}^{-2} \) and the hot plasma component temperature was fixed at \( kT_{\text{hot}} \approx 4.35 \text{ keV} \) as determined from EPIC pn fits. Subsolar abundances were adopted with \( \text{Fe} = 0.3 \) and \( \text{O} = 0.3 \times \text{ solar} \). In order to obtain sufficient flux to reproduce the \( \text{O VIII} \) line, cool component temperatures in the range \( kT_{\text{cool}} \approx 0.13 \text{--} 0.28 \text{ keV} \) \((T_{\text{cool}} \approx 1.5 \text{--} 3.2 \text{ MK})\) are required. These values are consistent with the accretion shock temperature estimated above. Even though accretion shock temperatures are favorable for producing \( \text{O VIII} \), the fraction of soft X-rays that could escape and be detected is sensitive to the line of sight absorption toward the shock region and photon escape becomes problematic at high infalling gas densities (Drake 2005).

**Cool Corona.** Coronal plasma in active low-mass stars is distributed over a wide range of temperatures and can include both a hot component \((T_{\text{hot}} \gtrsim 10 \text{ MK})\) as well as a cool component extending down to temperatures of \( T_{\text{cool}} \approx 3 \text{--} 4 \text{ MK} \). Two examples are the young solar analog EK Dra (Güdel et al. 1997) and the active binary II Peg (Huenemoerder et al. 2001), the latter showing a strong coronal \( \text{O VIII} \text{ Ly} \alpha \) line.

Electron density information derived from \( \text{O VIII} \) and \( \text{Ne} \times \) He-like triplets is typically used to discriminate between cool dense plasma in an accretion shock and cool lower-density coronal plasma. In RY Tau the \( \text{O VIII} \) and \( \text{Ne} \times \) triplets are only weakly detected if at all, so cool plasma density information is lacking. However, as we have noted, the slow variability seen in the Chandra very-soft and medium-band light curves mimics that of the hard-band (Figure 2), providing compelling evidence that some or all of the very-soft-band emission shares a common origin with the hard-band emission. The hard-band emission is undoubtedly associated with very hot plasma that cannot be reconciled with cool shocks and is thus presumably coronal, but possible contributions from the star-disk magnetic interaction region are not ruled out at the existing limits of X-ray telescope spatial resolution. By association, at least some of the cool plasma must also be of magnetic (non-shock) origin.

7. **SUMMARY**

We have presented new results clarifying the X-ray properties of the cTTS RT Tau based on observations obtained with Chandra and XMM-Newton. The main results of this study are the following:

1. The X-ray emission of RY Tau is strongly variable, consisting of intermittent rapid flares typical of coronal magnetic activity superimposed on slow light-curve modulation that may be tied to rotation of surface features across the line of sight.

2. The absorption column density \( N_{\text{H}} \approx (4 \text{--} 6) \times 10^{21} \text{ cm}^{-2} \) determined from X-ray spectral fits is comparable to or slightly larger than anticipated from \( L_{\text{V}} \).

3. The characteristic X-ray luminosity of RY Tau \( \log L_{\text{x}} \approx 30.65 \text{ erg s}^{-1} \) is among the highest of cTTS in Taurus but is nevertheless consistent with expectations based on its rather high mass and a known correlation between \( L_{\text{x}} \) and stellar mass in the Taurus cTTS population.

4. The X-ray EM distribution of RY Tau is dominated by hot plasma at characteristic temperatures of \( kT_{\text{hot}} \approx 4 \text{--} 5 \text{ keV} \) \((T_{\text{hot}} \sim 50 \text{ MK})\), but higher temperatures are recorded during flares. Flares give rise to fluorescent emission from neutral or near-neutral Fe at 6.4 keV arising from irradiated cold dense gas near the star. Gas in the accretion disk or accretion streams provides potential fluorescent target material.

5. A cool plasma component is present which varies slowly in lockstep with hotter plasma, providing a strong clue that at least some of the cool plasma is physically associated with the hotter plasma. Shocks cannot explain the very high temperatures of hot plasma which is undoubtedly associated with magnetic heating processes.
in the corona or perhaps in the star-disk magnetic interaction region. By association, at least some of the cool plasma is also of magnetic (non-shock) origin.

6. Any contribution to the X-ray EM from cool plasma \( (T_{\text{cool}} \lesssim 3 \text{ MK}) \) originating in the shocked jet or an accretion shock is small compared to the dominant hot plasma, but an accretion shock origin for the O VIII Ly\( \alpha \) line is not ruled out.

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