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## The Bipolar X-Ray Jet of the Classical T Tauri Star DG Tau

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**Abstract.** We report on new X-ray observations of the classical T Tauri star DG Tau. DG Tau drives a collimated bi-polar jet known to be a source of X-ray emission

perhaps driven by internal shocks. The rather modest extinction permits study of the jet system to distances very close to the star itself. Our initial results presented here show that the spatially resolved X-ray jet has been moving and fading during the past six years. In contrast, a stationary, very soft source much closer ( $\approx 0.15 - 0.2''$ ) to the star but apparently also related to the jet has brightened during the same period. We report accurate temperatures and absorption column densities toward this source, which is probably associated with the jet base or the jet collimation region.

## 1. Introduction

DG Tau is a classical T Tauri star (CTTS) with a flat infrared spectrum, indicating the presence of substantial circumstellar material. DG Tau ejects a well-studied bipolar jet, showing several knots and shocks (e.g., Eisloffel & Mundt 1998). The most prominent knots are presently located about  $5''$  and  $12''$  away from the star, toward the SW. The NE counter-jet is difficult to see owing to absorption/extinction by the foreground extended disk structure (Kitamura et al. 1996). We discovered DG Tau’s jet in X-rays (Güdel et al. 2005, 2007, 2008; G05, G07, resp. G08 henceforth) along with a spectral anomaly in the central source also ascribed to the jet. This anomaly manifests itself in a superposition of two unrelated spectral components subject to different hydrogen absorption column densities,  $N_{\text{H}}$ , in the unresolved central point spread function (PSF) that contains the star itself (defining a “Two-Absorber X-Ray Spectrum” = TAX, G07). The hard component is ascribed to the flaring corona/magnetosphere of the star, excessively absorbed by dust-depleted accretion streams, while the little absorbed soft component is ascribed to X-ray emission from the jet base. We have started a multi-wavelength campaign to study DG Tau in detail, centered around a Chandra Large Program (360 ks of ACIS-S time in January 2010, complementing our 90 ks obtained in 2004-06) and involving radio, millimeter, infrared, and optical telescopes. Here, we present initial results, focusing on the X-ray phenomenology.

## 2. Jet Morphology and Kinematics

The DG Tau X-ray jet is visible at PA=225 deg out to a distance of  $5-6''$ . Figure 1 is based on the January 2010 observations (360 ks). To optimize spatial resolution, we reconstructed events files for the detector’s “VFaint” mode (allowing for better background treatment), removing standard pixel randomization and applying the subpixel event repositioning (SER) method by Li et al. (2003) and Li et al. (2004). The image has been smoothed using a Gaussian kernel of width 1.2 pixels (1 pix =  $0.25''$ ), and intensity has been logarithmically compressed, including only 0.4-1.5 keV counts. The jet to the SW appears to be brightest toward its apex. This source coincides with an optical knot (see below). It is therefore likely that the gas has been heated by shocks forming in the jet.

The optical jet expands by  $0.15-0.3'' \text{ yr}^{-1}$  (Eisloffel & Mundt 1998; Dougados et al. 2000). The 2-color image in Fig. 2a shows a superposition of the (smoothed) X-ray data from Winter 2005/06 (green, 60 ks) and January 2010 (red). Jet motion is discernible. Using the wavdetect task in CIAO (on unsmoothed data), we find a velocity of  $\approx 0.2'' \text{ yr}^{-1}$  toward PA = 225 deg, coincident with the optical velocity. The X-ray shock regions are thus co-moving with the jet and are clearly not standing shocks.

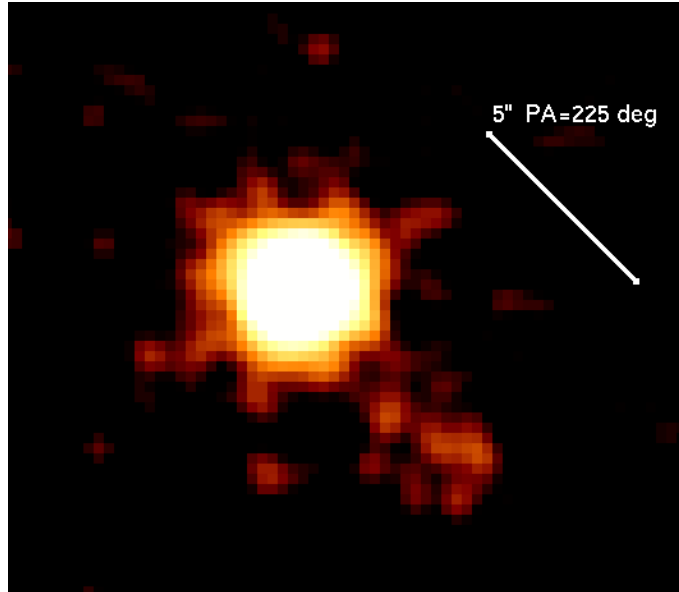


Figure 1. X-ray jet of DG Tau observed in January 2010, in the energy range 0.4–1.5 keV; the original data have been smoothed using a Gaussian kernel of width 1.2 pixels, where 1 pixel = 0.25".

The X-ray jet apparently faded between 2004 and 2010. X-ray count rates in identical areas of the SW jet were  $0.20 \pm 0.08 \text{ ct ks}^{-1}$  ( $1\sigma$ , 2004),  $0.18 \pm 0.06 \text{ ct ks}^{-1}$  (2006), and  $0.11 \pm 0.02 \text{ ct ks}^{-1}$  (2010), indicating a marginal trend consistent with cooling estimates in G08 for rather high electron densities (e.g.,  $10^5 \text{ cm}^{-3}$ ).

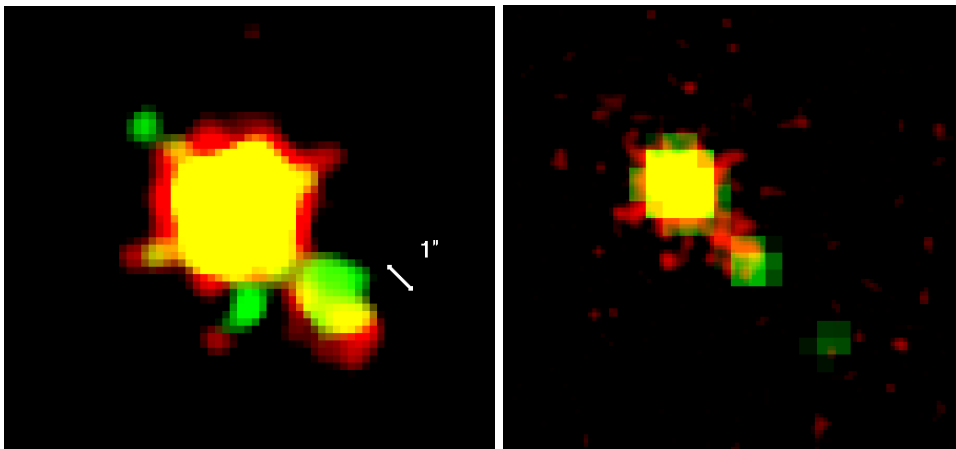


Figure 2. *Left* (a): Two-color image, showing superposition of smoothed X-ray images for Winter 2005/06 (green) and for January 2010 (red), indicating jet longitudinal motion. – *Right* (b): Calar Alto Potsdam Multi Aperture Spectrophotometer (PMAS) [S II] image (green) superimposed on a smoothed X-ray image (red).

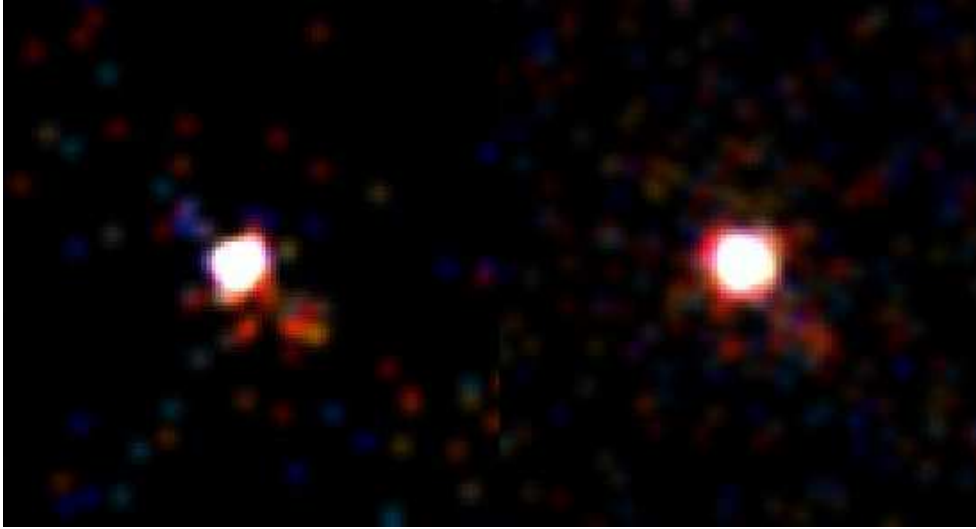


Figure 3. Smoothed hardness images of the DG Tau jet in 2004-2006 (left) and 2010 (right). Red is softest, blue hardest (for photons ranging from 0.5-1.5 keV). Note the absence of a significant counter-jet in 2010.

Figure 2b shows a superposition of X-rays (red) with blueshifted [S II] ( $-250 \text{ km s}^{-1}$  to  $-100 \text{ km s}^{-1}$ , green) observed with PMAS (Potsdam Multi Aperture Spectrophotometer) attached to the 3.5 m telescope at Calar Alto (mean seeing was  $1.8''$ , pixel size  $1'' \times 1''$ , observing date 16 November 2009). The [S II] knot is located at the tip of the soft X-ray jet.

### 3. The Counter-Jet

The 2004-06 Chandra data (90 ks) showed a clear X-ray detection of the counter jet (Fig. 3, left; 9 counts, see G08). Although still dominated by soft photons, its spectral appearance is harder than the forward jet. This has been ascribed to photoelectric absorption by the foreground extended disk. The excess  $N_{\text{H}}$  (compared to the forward jet) was found to be  $3 \times 10^{21} \text{ cm}^{-2}$ , compatible with the excess extinction toward the counter jet (G08). The image also shows – marginally – that the forward jet may be harder at its apex; this may be a sign of shock heating and post-shock cooling.

The counter-jet is hardly seen in the 4x longer 2010 exposure (Fig. 3, right) although we had expected to find 36 counts. The cause is unclear; most likely the jet has cooled by expansion and radiation (which is true for the forward jet as well – see below).

### 4. Closer to the Star: The Inner-Jet

The unresolved central point-spread function shows spectral TAX phenomenology, i.e., two unrelated thermal components subject to different absorption. The hard (1.5-7.3 keV) light curves (Fig. 4) and spectra (Fig. 5) show frequent flares, while the soft (0.5-1 keV) component is steady. However, the soft emission gradually increased from 2004

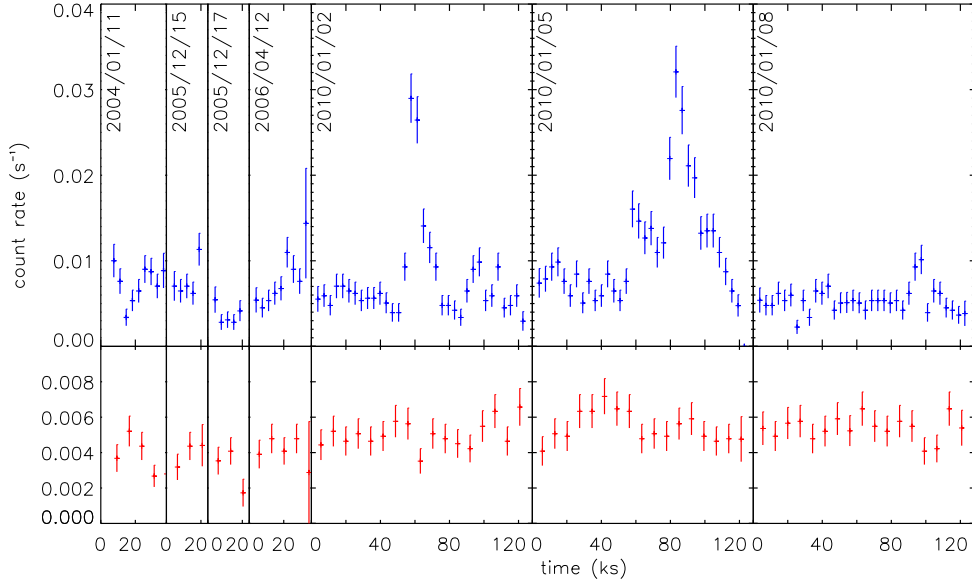


Figure 4. Hard (1.5–7.3 keV, upper panel) and soft (0.5–1.0 keV, lower panel) light curves extracted from the central PSF of all Chandra DG Tau observations; the individual observations are separated by vertical lines, and observing dates are given in the upper panels. Note the absence of correlated behavior in the two light curves and the nearly constant flux level in the soft emission except for a gradual increase in luminosity over 6 years, from  $1.1 \times 10^{29}$  erg s $^{-1}$  to  $1.8 \times 10^{29}$  erg s $^{-1}$ .

to 2010, corresponding to an increase of the X-ray luminosity from  $1.1 \times 10^{29}$  erg s $^{-1}$  (2004), to  $1.2 \times 10^{29}$  erg s $^{-1}$  (2006), to  $1.8 \times 10^{29}$  erg s $^{-1}$  (2010), while the temperature and absorption did not change.

The soft component indicates unusually low temperatures for X-ray sources in classical T Tauri stars. A 1-T thermal fit (using XSPEC/vapec) finds  $T = 3.7 \pm 0.2$  MK (90% errors), with  $N_{\text{H}} = (1.5 \pm 0.4) \times 10^{21}$  cm $^{-2}$ ; the latter is lower by a factor of 2–4 than expected from visual extinction (1.4–3.3 mag, G07); but, both values agree with the spectral energy distribution of the resolved jet (Fig. 6;  $T \approx 2.7[2.0 - 3.8]$  MK), suggesting that the soft component originates in the unresolved inner jet (G05). The soft image in Fig. 1 therefore shows only the jet - without the star!

Further support comes from a systematic offset between the soft (jet?) and the hard (star) PSF centroids, already described by Schneider & Schmitt (2008). We used CIAO tasks dmstat (confined to the central PSF) and wavdetect on the SER-treated images to derive offsets of 0.12''–0.16'' (dmstat), or 0.14''–0.20'' (wavdetect) in the jet direction – offsets much smaller than Chandra’s PSF. The 2-color image in Fig. 7 shows the hard (blue) vs soft (red) offset graphically, for the unsmoothed/smoothed PSF.

## 5. Summary

The DG Tau jet shows a rich X-ray phenomenology, including moving knots several arcseconds from the star itself but apparently also jet emission regions much closer to the star and unresolved in Chandra images. Observations taken over 6 years show an

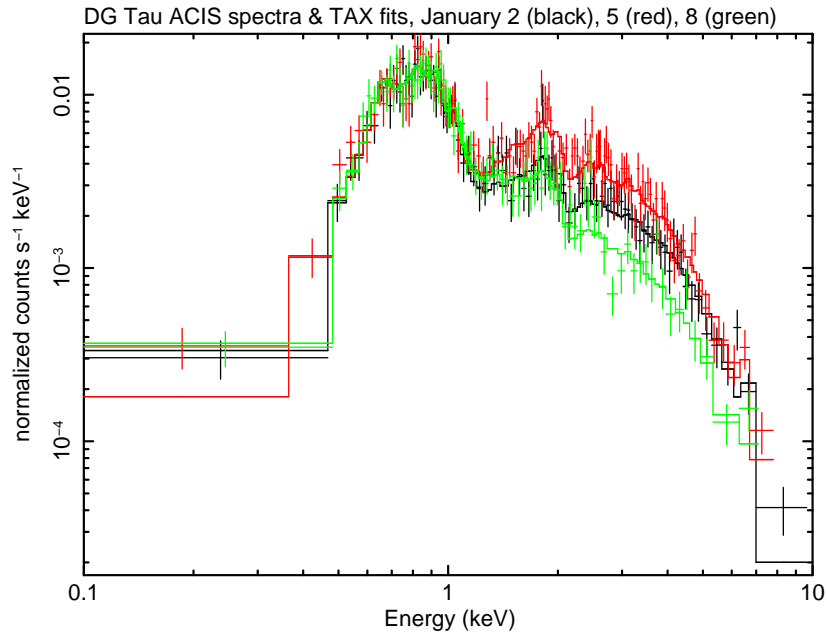


Figure 5. Chandra ACIS-S spectra of the DG Tau X-ray source in the central PSF. The spectra refer to observations taken on January 2 (black), January 5 (red), and January 8 (green), 2010. Note variability above 1.5 keV due to flares (see Fig. 4), but identical spectra below  $\approx 1.2$  keV.

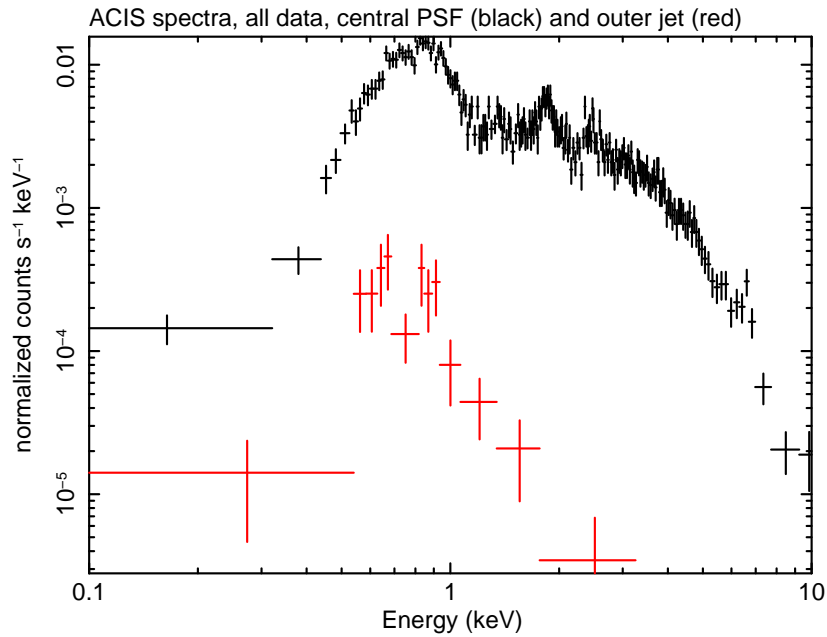


Figure 6. Spectrum of central Chandra PSF (black) and the outer, resolved jet (red). All available Chandra data were combined. Note similarity between jet spectrum and the soft peak of the central-PSF spectrum.

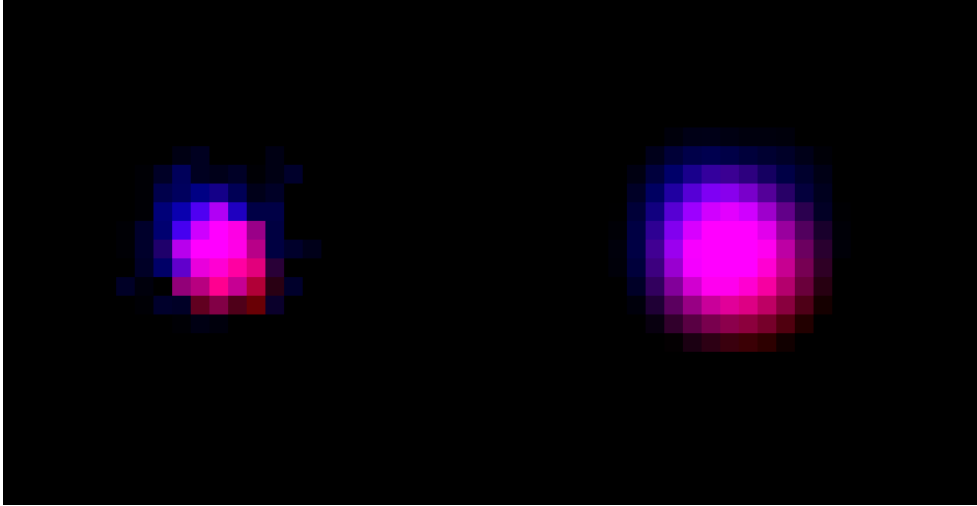


Figure 7. Two-color images illustrating the offset between the hard (1.5–7.3 keV, blue) and soft (0.45–1.1 keV, red) central PSFs for the combined 2010 observations. *Left*: unsmoothed, 1 pixel = 0.125". – *Right*: smoothed using Gaussian of width = 3 pixels, 1 pixel = 0.125".

apparent fading of the outer jet knots (and the near disappearance of the counter-jet), compatible with cooling models. On the other hand, the soft jet sources closer to the star has continuously brightened. We also measure X-ray jet motion in agreement with optical measurements. A more detailed interpretation of these data will be given in a forthcoming publication.

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