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Accretion and outflow-related X-rays in T Tauri stars

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Abstract. We report on accretion- and outflow-related X-rays from T Tauri stars, based on results from the "XMM-Newton Extended Survey of the Taurus Molecular Cloud." X-rays potentially form in shocks of accretion streams near the stellar surface, although we hypothesize that direct interactions between the streams and magnetic coronae may occur as well. We report on the discovery of a "soft excess" in accreting T Tauri stars supporting these scenarios. We further discuss a new type of X-ray source in jet-driving T Tauri stars. It shows a strongly absorbed coronal component and a very soft, weakly absorbed component probably related to shocks in microjets. The excessive coronal absorption points to dust-depletion in the accretion streams.

Keywords. Accretion, stars: activity, stars: coronae, stars: formation, stars: magnetic fields, stars: pre–main-sequence, stars: winds, outflows.

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1. Introduction

Classical and weak-lined T Tauri stars (CTTS and WTTS) are pre-main sequence stars showing vigorous X-ray emission with X-ray luminosities (L_X) near the empirical saturation limit found for main-sequence (MS) stars, $L_X/L_{bol} \approx 10^{-3.5}$. Consequently, X-ray emission from T Tauri stars has been attributed to solar-like coronal activity. However, both accretion and outflows/jets may contribute to or alter X-ray production in the magnetic environment of strongly accreting young stars. X-rays thus provide an important diagnostic for the detection and study of accretion and outflow activity.

Support for X-ray *suppression* in CTTS has been reported from X-ray photometry. CTTS are, on average, less X-ray luminous than WTTS (e.g., Strom & Strom 1994; Neuhäuser *et al.* 1995). This finding has been partly supported by recent, deep surveys of the Orion Nebula Cluster (Getman *et al.* 2005; Preibisch *et al.* 2005).

On the other hand, X-rays may be *generated* by surface accretion shocks (Lamzin 1999). If gas collides with the stellar photosphere in free fall, shocks heat it to a few million K. Given the appreciable accretion rates, high shock densities of order $10^{12} - 10^{14}$ cm^{-3} are expected, as first reported for the CTTS TW Hya (Kastner *et al.* 2002). X-rays may similarly be produced in shocks forming in jets (Raga *et al.* 2002).

The *XMM-Newton Extended Survey of the Taurus Molecular Cloud (XEST)* (Güdel *et al.* 2007a) has provided new insights into these issues. XEST covers the most populated ≈5 sq. deg of the Taurus star-forming region. The average on-axis detection limit is $\approx 10^{28}$ erg s^{-1} for lightly absorbed objects, sufficient to detect about half of the observed brown dwarfs (Grosso *et al.* 2007a). We discuss X-ray results relevant for the star-disk interface in which accretion occurs and where (parts of) the jets may be accelerated.

2. Accretion and the "X-ray Soft Excess"

2.1. *Accretors in XEST*

Telleschi *et al.* (2007a) present statistical X-ray studies of the XEST CTTS and WTTS samples. The WTTS sample is essentially complete (all but one of the 50 surveyed objects detected), and the CTTS sample is nearly complete (85% of the 65 surveyed objects detected). The luminosity deficiency of CTTS is confirmed. More precisely, CTTS are statistically less luminous by a factor of ≈ 2 both in L_X and in L_X/L_{bol} (Fig. 1a) while the L_{bol} distributions of the two samples are drawn from the same parent population.

On the other hand, Telleschi *et al.* (2007a) report the average electron temperature, T, in the X-ray sources of CTTS to be higher than in WTTS, irrespective of the gas absorption column density (N_H). For WTTS, a trend also seen in MS stars is recovered, in the sense that the electron temperature increases with L_X. Such trends are expected in stochastic-flare heated coronae (Telleschi *et al.* 2005), but a similar trend is absent in CTTS in which the average temperature remains high for all activity levels.

In contrast to the apparent X-ray deficiency, a trend toward an ultraviolet excess is found in CTTS based on the Optical Monitor (OM) data (Audard *et al.* 2007). The UV excess supports an accretion scenario in which gas in accretion streams shock-heats near the surface to form hot spots (Calvet & Gullbring 1998). The OM has also recorded a slow U-band flux increase in a brown dwarf, most likely due to an "accretion event" covering a time span of several hours (Grosso *et al.* 2007b).

Accretion shocks may leave signatures in line-dominated high-resolution X-ray spectra. Given the typical mass accretion rates on T Tauri stars and their modest accretion hot spot filling factors of no more than a few percent (Calvet & Gullbring 1998), densities of order 10^{12} cm^{-3} or more are to be expected (Telleschi *et al.* 2007c; Güdel *et al.* 2007c),

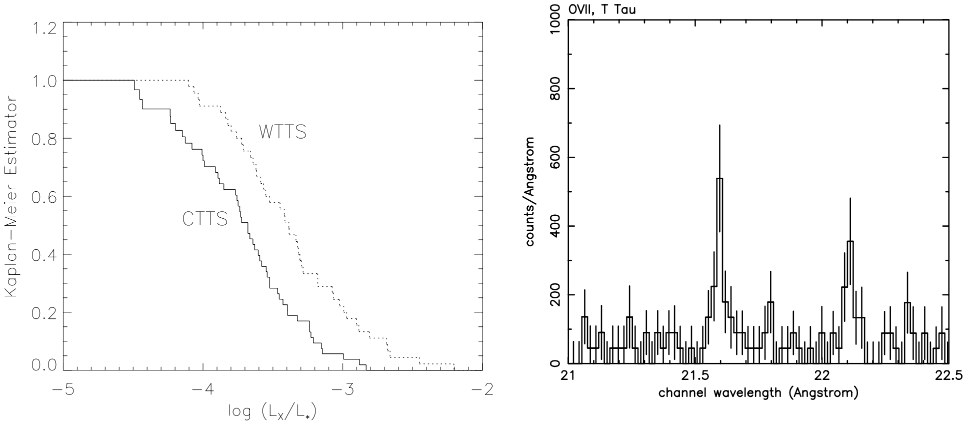

Figure 1. *Left (a)*: The cumulative distribution of the L_X/L_{bol} ratio for CTTS (solid) and WTTS (dotted) are different at the $>$ 99.97% level (from Telleschi *et al.* 2007a). – *Right (b)*: The O VII triplet of T Tau, showing a strong forbidden line at 22.1 Å (after Güdel *et al.* 2007c).

and such densities are indeed indicated in the density-sensitive line ratios of O VII and Ne IX triplets of some CTTS (e.g., Kastner *et al.* 2002; Stelzer & Schmitt 2004). XEST has added relevant information on two further accreting pre-main sequence stars: T Tau N (Güdel *et al.* 2007c) and the Herbig star AB Aur (Telleschi *et al.* 2007b). However, in both *XMM-Newton* RGS spectra, the O VII triplet line ratios are compatible with density upper limits of a few times 10^{10} cm^{-3} (Fig. 1b), apparently not supporting the accretion-shock scenario. How important really is accretion for CTTS X-ray emission?

2.2. *The "X-Ray Soft Excess"*

Fig. 2 compares *XMM-Newton* RGS spectra of the active binary HR 1099 (X-rays mostly from a K-type subgiant; archival data) the weakly absorbed WTTS V410 Tau (Telleschi *et al.* 2007c), the CTTS T Tau (Güdel *et al.* 2007c), and the old F subgiant Procyon (archival data). HR 1099 and V410 Tau show the typical signatures of a hot, active corona such as a strong continuum, strong lines of Ne X and of highly-ionized Fe but little flux in the O VII line triplet. In contrast, lines of C, N, and O dominate the soft spectrum of Procyon, the O VII triplet exceeding the O VIII Lyα line in flux. T Tau reveals signatures of a very active corona shortward of 19 Å but also an unusually strong O VII triplet. Because its N_H is large (in contrast to N_H of V410 Tau), we have modeled the intrinsic, unabsorbed spectrum based on transmissions determined in XSPEC using N_H from EPIC spectral fits ($N_H \approx 3\times10^{21}$ cm^{-1}; Güdel *et al.* 2007a). *The* O VII *lines are the strongest lines in the intrinsic X-ray spectrum,* reminiscent of the situation in Procyon!

To generalize this finding, we plot in Fig. 3 the ratio between the intrinsic (unabsorbed) luminosities of the O VII r line and the O VIII Lyα line as a function of L_X, comparing CTTS and WTTS with a larger MS sample (Ness *et al.* 2004) and MS solar analogs (Telleschi *et al.* 2005). The TTS data are from Robrade & Schmitt (2006), Günther *et al.* (2006), Argiroffi *et al.* (2007), Telleschi *et al.* (2007c), and from our analysis of archival *XMM-Newton* data of RU Lup. For the TTS sample given by Telleschi *et al.* (2007c), we have approximated $L(\text{O VII } r) = 0.55L(\text{O VII})$ (Porquet *et al.* 2001). The trend for MS stars (black crosses and triangles, § 2.1) is evident: as the coronae get hotter toward higher L_X, the ratio of O VII r/O VIII Lyα line luminosities decreases. This trend is followed by the sample of WTTS, while CTTS again show a significant excess. This is the essence of the *X-ray soft excess* in CTTS first discussed by Telleschi *et al.* (2007c) and Güdel

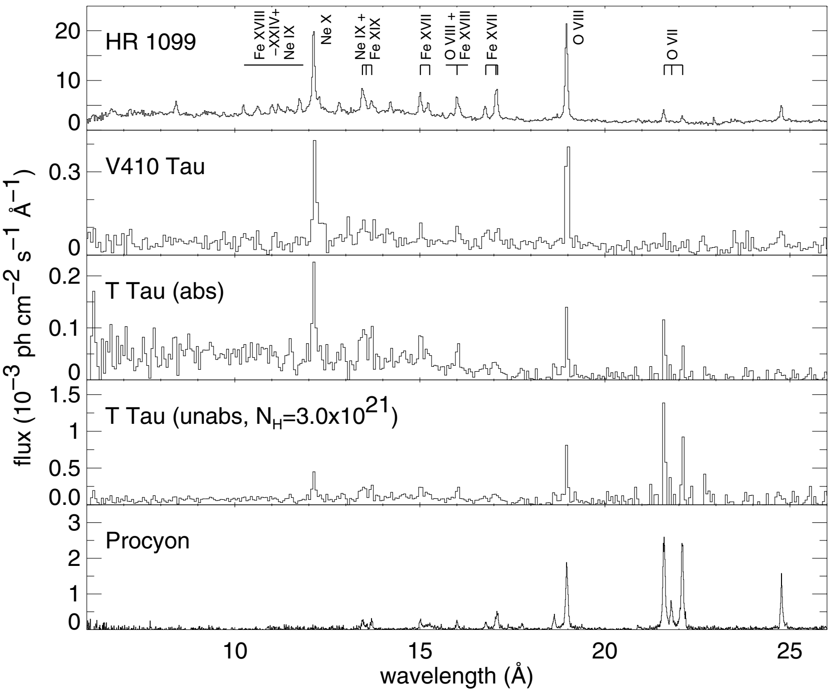

Figure 2. Comparison of fluxed *XMM-Newton* RGS photon spectra of (from top to bottom) the active binary HR 1099, the WTTS V410 Tau, the CTTS T Tau, T Tau modeled after removal of absorption, and the inactive MS star Procyon. The bins are equidistant in wavelength.

et al. (2007c): *accreting pre-main sequence stars reveal a strong excess of cool (1-2 MK) material, regardless of the overall X-ray deficiency at higher temperatures.*

2.3. *Summary and conclusions on accretion-related X-ray emission*

Crucial XEST results on X-ray production and accretion can be summarized as follows:

1. Accreting CTTS show a general deficiency in X-ray production when referring to the hot coronal gas recorded by X-ray CCD cameras (Telleschi *et al.* 2007a);
2. the average coronal T is higher in CTTS than in WTTS (Telleschi *et al.* 2007a);
3. All CTTS (except the two flaring sources SU Aur [also subject to high $N_{\rm H}$] and DH Tau) show a *soft excess* defined by an anomalously high ratio between the fluxes of the O VII He-like triplet and the O VIII Lyα line, when compared to WTTS and MS stars.

The origin of the additional cool plasma in CTTS is likely to be related to the accretion process. Accretion streams may shock-heat gas at the impact point to X-ray emitting temperatures. This model is supported by high electron densities inferred from the observed O VII or Ne IX triplets in some of the CTTS (e.g., Kastner *et al.* 2002; Stelzer & Schmitt 2004), although high densities were not seen in the two XEST accretors T Tau (Güdel *et al.* 2007c) and AB Aur (Telleschi *et al.* 2007b). Alternatively, the cool, infalling material may partly cool pre-existing heated coronal plasma, or reduce the efficiency of coronal heating in the regions of infall (Preibisch *et al.* 2005; Telleschi *et al.* 2007c; Güdel *et al.* 2007c). This model would at the same time explain why CTTS are X-ray weaker than WTTS (Preibisch *et al.* 2005; Telleschi *et al.* 2007a). We cannot assess what the relative importance of these processes is. It seems clear, however, that the soft excess described here argues in favor of a substantial influence of accretion on the X-ray production in pre-main sequence stars.

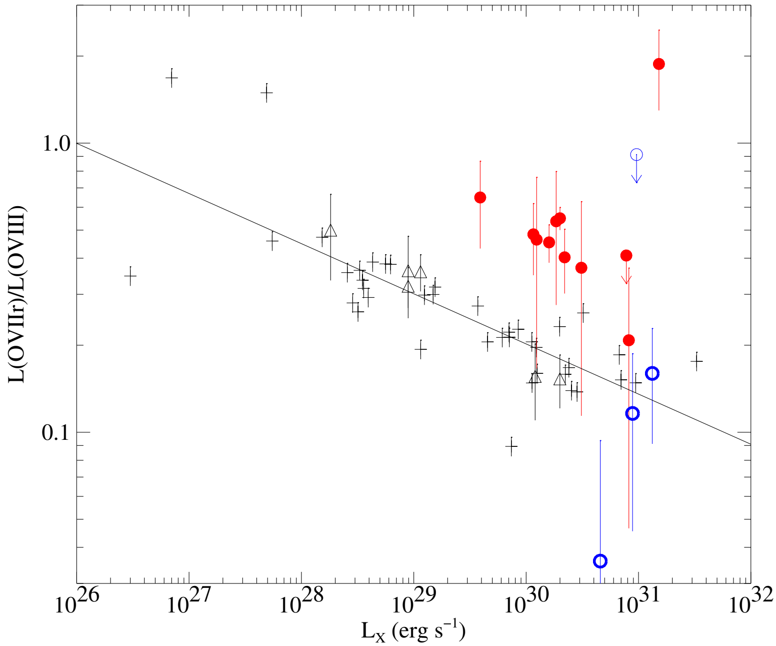

Figure 3. The ratio between O VII r and O VIII Lyα luminosities (each in erg s^{-1}) vs. the total L_X. Crosses mark MS stars, triangles solar analogs of different ages, filled (red) circles CTTS, and open (blue) circles WTTS. The solid line is a power-law fit to the MS stars (after Güdel & Telleschi 2007, submitted).

3. Outflow-related X-rays

The shock temperature in jets can be expressed as $T \approx 1.5 \times 10^5 v_{100}^2$ K (for fully ionized gas) where v_{100} is the shock speed in units of 100 km s^{-1} (e.g., Raga *et al.* 2002). Jet speeds are typically of order $v = 300 - 500$ km s^{-1} (Eislöffel & Mundt 1998; Anglada 1995; Bally *et al.* 2003), in principle allowing for shock speeds of similar magnitude.

Faint, soft X-ray emission has been detected from a few protostellar HH objects (Pravdo *et al.* 2001, Pravdo *et al.* 2004; Pravdo & Tsuboi 2005; Favata *et al.* 2002; Bally *et al.* 2003; Tsujimoto *et al.* 2004; Grosso *et al.* 2006). Bally *et al.* (2003) used a *Chandra* observation to show that X-rays form within an arcsecond of the protostar L1551 IRS-5 while the star itself is too heavily obscured to be detected. Strong absorption and extinction of protostars and their immediate environment make the launching region of their powerful jets generally inaccessible to optical, near-infrared, or X-ray studies. However, a class of strongly accreting, optically revealed CTTS also exhibit so-called micro-jets visible in optical lines (Hirth *et al.* 1997), with flow speeds similar to protostellar jets. CTTS micro-jets have the unique advantage that they can – in principle – be followed down to the acceleration region both in the optical and in X-rays.

3.1. *"Two-Absorber X-Ray" (TAX) Sources*

X-ray spectra of very strongly accreting, micro-jet driving CTTS exhibit an anomaly (Fig. 4, Güdel *et al.* 2005; Güdel *et al.* 2007b): the spectra of DG Tau, GV Tau, DP Tau, CW Tau, and HN Tau are composed of two components, a cool component subject to very low absorption and a hot component subject to photoelectric absorption about one order of magnitude higher. For similar phenomenology, see also Kastner *et al.* (2005) and Skinner *et al.* (2006). The cool component shows temperatures atypical for T Tau stars,

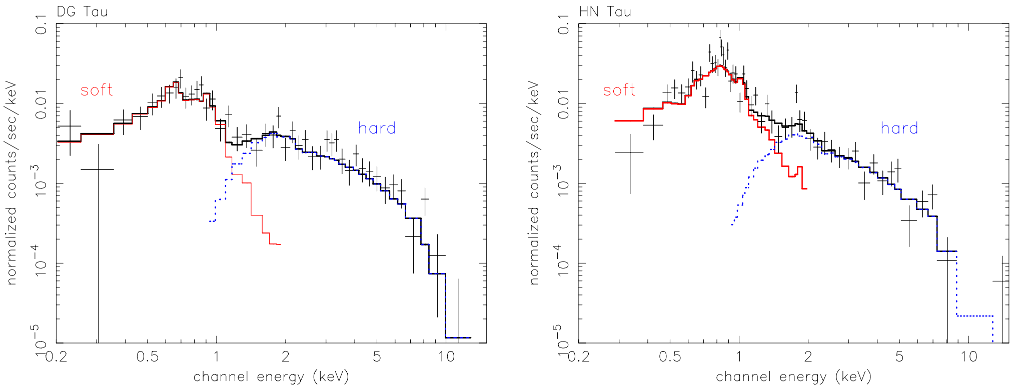

Figure 4. *XMM-Newton* EPIC PN spectra of the jet sources DG Tau (left) and HN Tau (right). The red (solid) and blue (dotted) histograms show the spectral fits pertaining to the soft and hard component, respectively (DG Tau after Güdel *et al.* 2007b).

ranging from $\approx 3-6$ MK, while the hot component reveals extremely high temperatures (10–100 MK). We discuss in the following the best example, the single CTTS DG Tau.

The hard spectral component of the DG Tau point source is unusually strongly absorbed, with a gas column density ($N_{\rm H} \approx 2\times 10^{22}$ cm^{-2}) higher by a factor of ≈ 5 than predicted from the visual extinction $A_{\rm V}$ of 1.5–3 mag if standard gas-to-dust ratios are assumed (see Güdel *et al.* 2007b and references therein). Because the hard component occasionally flares, in one case being preceded by U band emission as in solar and stellar flares (Güdel *et al.* 2007b), it is most straightforwardly interpreted as coronal or "magnetospheric". The *excess absorption* is likely to be due to the heavy accretion streams falling down along the magnetic fields and absorbing the X-rays from the underlying corona/magnetosphere. The excess absorption-to-extinction ($N_{\rm H}/A_{\rm V}$) ratio then is an indicator of dust sublimation: *the accreting gas streams are dust-depleted.*

In contrast, $N_{\rm H}$ of the soft X-ray component, $N_{\rm H} = 1.3\ (0.7-2.4)\times 10^{21}$ cm^{-2} (90% error range) is *lower* than suggested from the stellar $A_{\rm V}$, $N_{\rm H}(A_{\rm V}) \approx (3-6)\times 10^{21}$ cm^{-2}. A likely origin of these X-rays is the base of the jet. Such an origin is suggested by i) the unusually soft emission not usually seen in T Tauri stars (Güdel *et al.* 2007a), ii) the low $N_{\rm H}$, and iii) the explicit evidence of jets in the *Chandra* image, as we will show below.

3.2. *X-rays and jets*

A *Chandra* X-ray image of the DG Tau environment is shown in Fig. 5b (pixel size 0.49″). This image was produced by combining counts from a total of 90 ks of *Chandra* exposure time. Also shown is a smoothed version. To suppress background and to emphasize the soft sources, only counts within the 0.6–1.7 keV range are plotted. There is clear evidence for a jet-like extension outside the stellar point spread function (PSF) to the SW along a position angle of ≈ 225 deg, but we also find a significant excess of counts in the NE direction (PA ≈ 45 deg). This is coincident with the jet optical axis, which for the SW jet has been given as 217-237 deg (Eislöffel & Mundt 1998). We verified, using raytrace simulations, that the jet sources are extended: a faint point source would occupy only a few pixels. We also find the counter jet to be harder, with photon energies mostly above 1 keV, while the forward jet shows a mixture of softer and harder counts. The spectral properties of the jet sources are reminiscent of the *soft* component in the "stellar" spectrum.

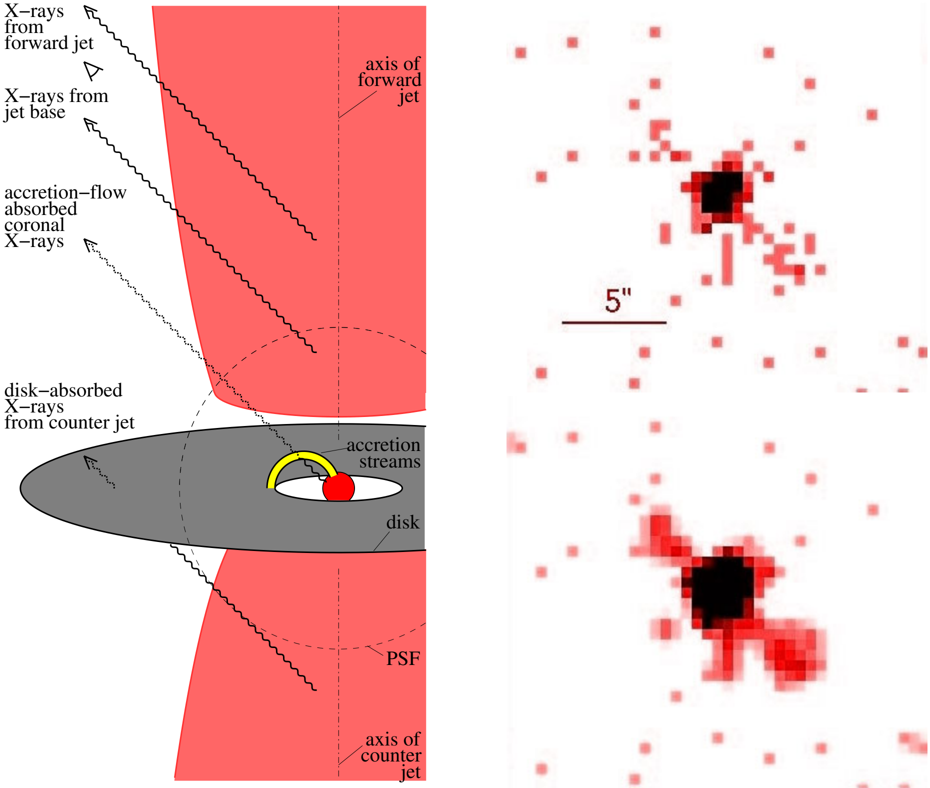

Figure 5. *Left (a):* Proposed model for the disk-jet interface with various X-ray sources, including: the spatially resolved forward jet; the spatially unresolved (within the stellar PSF) but spectrally resolved sources at the jet base; the accretion-stream absorbed corona/magnetosphere; and the disk-absorbed counter-jet sources. – *Right (b)*: Two *Chandra* ACIS-S 0.6–1.7 keV images of DG Tau and its jets; the lower figure has been smoothed (after Güdel *et al.* 2007, submitted).

3.3. *Summary on jets*

DG Tau is the prototype of a new class of jet-driving X-ray sources. It hosts at least four X-ray sources of different origin and subject to different $N_{\rm H}$ (see Fig. 5a), namely:

1. a weakly absorbed, diffuse, soft component along the forward-jet axis;
2. an intermediately absorbed, diffuse, soft component along the counter-jet axis;
3. a weakly absorbed, compact, non-variable, soft component (within the stellar PSF);
4. a strongly absorbed, compact, flaring, hard component (within the stellar PSF).

The low $N_{\rm H}$ of the *forward jet* and of the *soft stellar* component suggests that the soft spectral emission originates from a region "in front" of the star. We identify the soft component with X-ray emission from the base of the jets. In contrast, the harder *counter jet* suggests stronger absorption by the extended gas disk. A determination of the gas-to-dust ratio is in principle possible by measuring the differential absorption and extinction of the two jets. Finally, the *hard stellar* component is attributed to a (flaring) corona, with the excess photoelectric absorption due to dust-depleted accretion gas streams.

The combined power of the resolved jets and the unresolved soft spectral component is of order 10^{29} erg s^{-1}, similar to the X-ray output of a moderate T Tauri star. This emission, distributed above the accretion disk, may be an important contributor to X-ray heating and ionization of gaseous disk surfaces (Glassgold *et al.* 2004). We speculate that protostellar jets in general develop the same kind of jet X-ray emission, but these sources remain undetected close to the star because of strong photoelectric absorption.

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