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High-energy radiation and particles in the environments of young stellar objects

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Abstract. High-energy radiation and particles profoundly affect circumstellar disk gas and solids. We discuss stellar high-energy sources and summarize their effects on circumstellar disks.

Keywords. Young stellar objects, X-rays, high-energy particles, ionization

1. Circumstellar disks subject to high-energy radiation and particles

Stellar X-rays may heat circumstellar disks to > 1000 K at AU distances, as suggested by, e.g. H_2 2.12μm (Bary *et al.* 2003) and CO fundamental+overtone emission (Najita *et al.* 2003). X-rays may also ionize disks more efficiently than cosmic rays at similar distances, thus driving accretion through the magnetorotational instability (Glassgold *et al.* 1997). They may further dominate disk photoevaporation in the 10–40 AU range, resulting in mass loss rates of order 10^{-9} $M_\odot$ yr^{-1} (Ercolano *et al.* 2009).

What high-energy photons do reach the disk surface at all? Average neutral gas column densities around classical T Tauri stars (CTTS, $N_{\rm H} \approx 10^{21} - 10^{22}$ cm^{-2}, Güdel *et al.* 2007a) typically exceed those of weak-lined T Tauri stars, suggesting excess gas located relatively close to the star. This gas easily absorbs EUV radiation, as do disk winds (Hollenbach & Gorti 2009), questioning the role of EUV radiation in CTTS disks. Absorption may be even more severe in some strong accretors where accretion streams seem to absorb all X-rays below $\approx 1 - 2$ keV (Güdel *et al.* 2007b).

Increasing X-ray absorption with increasing disk inclination provides, nevertheless, direct evidence for disk ionization (Kastner *et al.* 2005). Further support comes from fluorescent 6.4 keV Kα emission from "cold" iron at the disk surface during strong flares (Imanishi *et al.* 2001). Fluorescence may reach extremely high levels in protostars even outside any obvious flaring (Skinner *et al.* 2007).

The [Ne II] 12.81μm line, frequently detected in *Spitzer* spectra (Pascucci *et al.* 2007), may be another diagnostic for X-ray/EUV disk irradiation (Glassgold *et al.* 2007). A statistically significant correlation with the stellar X-ray luminosity is, however, dominated by scatter (Figure 1a); obviously, a number of further parameters (e.g., disk properties) are relevant. For example, the presence of jets leads to a large increase in [Ne II] luminosity (Fig. 1b) as also shown in spatially resolved observations (van Boekel *et al.* 2009).

Glauser *et al.* (2009) found dust crystallinity to anti-correlate with the central star's X-ray luminosity. Although X-rays carry insufficient momentum to induce lattice displacements, energetic (several keV) particles in the stellar wind are held responsible for amorphizing circumstellar dust.

2. What high-energy sources?

Apart from "traditional" magnetic coronae, additional high-energy sources have been identified. While accretion "suppresses" coronal X-rays by a factor of ≈ 2 (Telleschi *et al.*

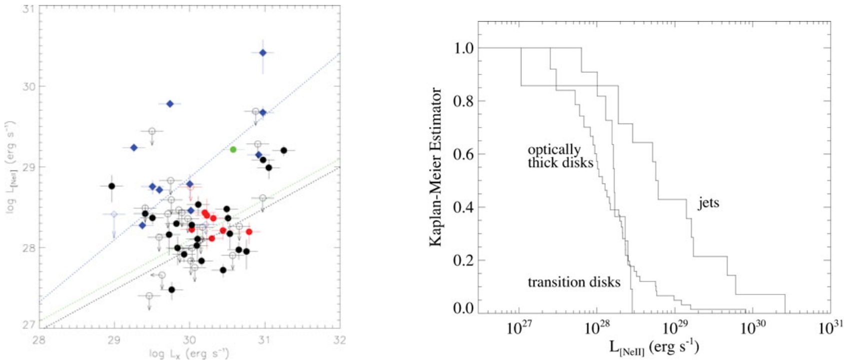

Figure 1. *Left (a):* [Ne II] luminosity vs. X-ray luminosity for CTTS; jet sources are shown by diamonds, disks without jets by circles (filled: detections; open: upper limits). *Right (b):* Kaplan-Meier estimator for the [Ne II] luminosity of CTTS disks without jets, CTTS jet sources, and transition disks. From Güdel *et al.* (2009).

2007), it adds a "soft excess" at cool (coronal) temperatures (Güdel & Telleschi 2007), perhaps due to an interaction between accretion streams and the corona. High densities inferred from X-ray line triplets (Kastner *et al.* 2002) have successfully been modeled in terms of shocks at the footpoints of accretion streams (Günther *et al.* 2007). CTTS jets also emit X-rays close to the star (Güdel *et al.* 2007b). Their "lamp-post" arrangement may provide ideal illumination of disk surfaces, avoiding absorption by accretion streams.

Large flares are of interest as they produce hard X-rays and may eject more energetic particles. Disks may thus be ionized more efficiently to deeper levels (Ilgner & Nelson 2006). However, as the energetics of X-ray emission appear to be dominated by the large population of *small* flares (Audard *et al.* 2000), hard X-rays should be continuously present, adding as yet unrecognized ionization power to the circumstellar environment.

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