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Protoplanetary disks and hard X-rays

Eric D. Feigelson[1], Philip J. Armitage[2,3] and Konstantin V. Getman[1]

[1]Dept. of Astronomy and Astrophysics, Penn State University, University Park PA 16802
[2]JILA, Campus Box 440, University of Colorado, Boulder CO 80309
[3]Dept. of Astrophysical and Planetary Sciences, University of Colorado, Boulder CO 80309

The physics of protoplanetary disks and the early stages of planet formation is strongly affected by the level of ionization of the largely-neutral gas (Armitage 2009; Balbus 2009). Where the ionization fraction is above some limit around $\sim 10^{-12}$, the magnetorotational instability (MRI) will ensue and the gas will become turbulent. The presence or absence of disk turbulence at various locations and times has profound implications for viscosity, accretion, dust settling, protoplanet migration and other physical processes. The dominant source of ionization is very likely X-rays from the host star (Glassgold *et al.* 2000). X-ray emission is elevated in all pre-main sequence stars primarily due to the magnetic reconnection flares similar to, but much more powerful and frequent than, flares on the surface of the contemporary Sun (Feigelson *et al.* 2007).

Most theoretical studies of the ionization of X-rays into the circumstellar disk assume simplistic models for the X-ray spectrum with relatively soft spectra. But hard X-rays penetrate much deeper into the disk and will be critical for determining the extent of the Dead Zone where turbulence is absent. Ilgner & Nelson (2006) show that flares with plasma temperatures $kT = 7$ keV produce ~ 1000 times higher ionization at the disk midplane than flares with $kT = 3$ keV. Getman *et al.* (2008) study hundreds of strong X-ray flares in Orion Nebula stars and find that peak temperatures range from 1 to > 20 keV; the latter are nicknamed 'superhot' flares. Recalling that a significant flux of photons will be present at even higher energies, we are motivated to investigate the effect of hard X-ray irradiation on protoplanetary disks.

We have constructed a time-dependent protoplanetary disk model subject to X-ray ionization with layered Active and Dead Zones. X-ray spectrum, disk viscosity, recombination rate, and the critical Reynolds number for onset of the MRI are model parameters. For all X-ray inputs, the model reproduces observed accretion rates in pre-main sequence stars, declining from 10^{-7} $M_{\odot}$/yr at ages ~ 0.1 Myr to $\sim 10^{-10}$ at ~ 3 Myr. However, the presence of hard X-ray irradiation considerably changes disk structure, increasing surface density in the Dead Zone. This may promote the formation of planets in the Dead Zone.

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