X-rays from Pre-Main Sequence Stars: Recent Results and Future Challenges

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Abstract

I summarize recent results of X-ray observations of pre-main sequence (PMS) stars, focusing on XMM-Newton RGS and Chandra HETG observations of RY Tau. These observations provide the best grating spectra obtained so far of a jet-driving T Tauri star. I also identify key questions regarding the origin and nature of X-ray emission from PMS stars that have emerged from 16 years of XMM-Newton and Chandra observations and which present challenges for the next decade.

1 RY Tau

- An X-ray bright intermediate mass classical T Tauri star driving an optical jet traced out to 31$''$ from star along P.A. $\approx$ 295° (St.-Onge & Bastien 2008 [SB08]).
- A 2009 *Chandra* ACIS-S observation (no gratings) shows soft X-ray emission outward along optical jet axis (Fig. 1).
- Binarity suspected, but no companion yet found.

Sp. Type	d (pc)	Age (My)	Mass ($M_\odot$)	L_{bol} ($L_\odot$)	log L_x (ergs/s)
G1-F8	134	$\sim$6.5	1.7 - 2.0	$\sim$15	30.8$\pm$0.3 (v)

2 RY Tau Jet

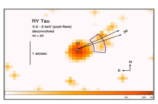

FIGURE 1: Deconvolved soft-band *Chandra* ACIS-S X-ray image from previous 2009 observation without gratings (Skinner et al. 2011). The arrows of length 1.7 arcsec show the range P.A. = 292 - 299 deg. of the optical jet from emission knots (SB08). Faint X-ray emission is seen extending out to $\approx$1.7 arcsec, overlapping the optical jet. Some of the X-ray emission inside the sectored region (0.6 $\leq$ r $\leq$ 1 arcsec) may be due to PSF asymmetry.

3 RY Tau Grating Observations

- *XMM* RGS, 92 ks, 21-22 Aug. 2013
- *Chandra* ACIS-S/HETG, 109 ks, 22-24 Oct. 2014
- Details: Skinner, Audard, & Güdel 2016 (SAG16)

4 RY Tau Strong X-ray Variability

- XMM: Rapid variability, typical of magnetic flares (Fig. 2-left)
- Chandra: Slow decay/rise; similar variability in soft and hard bands (Fig. 2-right).
- Slow decay/rise may be rotation-related

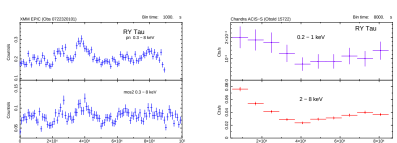

FIGURE 2: X-ray light curves of RY Tau (SAG16). Left: *XMM* EPIC pn (top) and MOS2 (bottom) (0.3-8 keV). Right: *Chandra* ACIS-S very-soft (0.1 - 1 keV) and hard (2 - 8 keV) bands on 22-23 Oct. 2014 (85 ks).

5 RY Tau CCD X-ray Spectra

- Spectrum variable; harder during flares (Fig. 3-left).
- Hot plasma dominates, even outside of flares.
- During flares, $kT_{hot} \geq$ 8-9 keV ($T_{hot} \geq$ 100 MK).
- Absorption below 0.5 keV masks cool plasma.
- Fluorescent Fe emission (6.4 keV) present during flares (Figs. 3-right), arising in cold material near star.

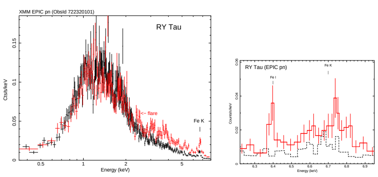

FIGURE 3: Left: *XMM* EPIC pn spectra of RY Tau during flare (red) and non-flare (black) time intervals (SAG16). Right: Zoom showing fluorescent Fe emission during flare (red) arising in cold material near star (e.g. accreting gas or disk gas) irradiated by hard flaring X-ray source (SAG16).

6 RY Tau Grating X-ray Spectra

- Low and high-T lines present (Fig. 4).
- Numerous Fe lines. Fe abundance strongly subsolar.
- Si XIII and Mg XI He-like triplets detected.
- Ne IX He-like triplet weak or absent.

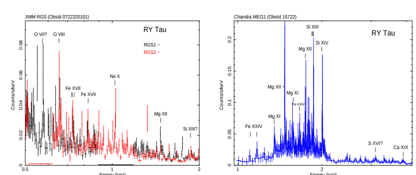

FIGURE 4: RY Tau X-ray grating spectra (SAG16). Left: Lightly-binned *XMM* RGS 1st order grating spectra of RY Tau for the full exposure (flare+non-flare segments). Right: Binned 1st order *Chandra* MEG spectrum of RY Tau.

7 RY Tau Summary

- The hard flaring component is of magnetic origin (i.e. hot coronal plasma or perhaps star-disk interaction region).
- Persistent X-ray variability indicative of a highly-dynamic magnetic environment. Rapid rotation: $v\sin i \approx$ 50 km s^{-1}.
- Slow variability (Fig. 2-right) is similar in very soft (0.2 - 1 keV) and hard (2 - 8 keV) bands, suggesting that some of the cool plasma shares a common (magnetic) origin with the hot plasma. Rotation of surface inhomogeneities across the line-of-sight may be involved.

8 Future Challenges: PMS Stars

- How are YSO X-ray jets heated to X-ray temperatures of a few MK? Recent studies suggest that shocks alone may not be sufficient (e.g. Skinner et al. 2011). Other possibilities are magnetic heating within the jet and stellar heating (and ionization) at the base of the jet.
- Where do hard X-rays originate in accreting TTS and protostars? Exclusively in magnetospheric (coronal-like) structures or does hard X-ray production also occur in the star-disk magnetic interaction region?
- What is the origin of slow X-ray variability detected in some TTS like RY Tau? Rotational modulation associated with solar-like active regions? Do non-solar phenomena such as accretion footpoints also induce slow X-ray modulation?
- In most PMS stars, fluorescent Fe I emission (6.4 keV) is associated with hard X-ray flares. But in some objects like NGC 2071 IRS1 a strong Fe I line is present even in the absence of hard X-ray flares and with only very faint hard continuum emission detected above 7 keV (Skinner et al. 2009). What (and where) is the hard ionizing source in such objects?
- What is the origin of the very high X-ray absorption seen toward some rapidly-accreting PMS stars. For example, X-ray spectral fits of FU Ori yield $N_H \sim 10^{23}$ cm^{-2} (equivalent to $A_V \sim$ 50 mag) while its optical extinction is much lower ($A_V \sim$ 2 mag). Are the softer X-rays absorbed by the accretion stream? Cool winds?
- What is the cumulative effect of hard X-ray flares and associated high particle fluxes in PMS on the early development of close-in exoplanets ($\sim$few AU) and their atmospheres?

LkCa 15 [Work in progress] The TTS LkCa 15 is believed to harbor one or more protoplanets (Kraus & Ireland 2012). We previously modeled the X-ray disk heating and ionization of LkCa 15 based on a *Chandra* ACIS-S spectrum (Fig.5). We are now extending this work using new higher S/N *XMM* EPIC data (Fig. 5-left; Skinner & Güdel, in prep.).

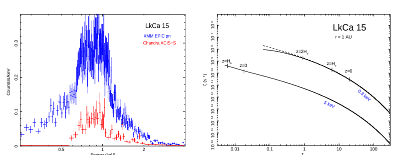

FIGURE 5: Left: CCD X-ray spectra of the TTS LkCa15 from *Chandra* ACIS-S (red, 586 cts; Skinner & Güdel 2013) and *XMM-Newton* EPIC pn (blue, 8994 cts; Skinner & Güdel, in prep.). Right: Ionization rate for the cool and hot plasma components as a function of X-ray optical depth for LkCa 15 at a radial distance r = 1 AU (*Chandra* ACIS-S analysis; Skinner & Güdel 2013). The short vertical lines mark the optical depth at the disk midplane (z = 0) and at multiples of one scale height (H_O) for each component.

References & Acknowledgment

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