IM LUP COMES TO AGE: A TURNOVER FROM ACCRETION TO CORONAE?

1 Abstract

We propose to obtain a *Chandra*/HETGS spectrum of IM Lup with an exposure of 150 ks. IM Lup is the only known X-ray bright transition object between the classical T Tauri star phase and the weak-lined T Tauri phase. IM Lup shows an IR excess, but its Hα equivalent width is small, indicating very low accretion rates. The *Chandra* spectrum will provide important information on the accretion process during the last stages of disk dispersal and therefore the latest possible time for planet growth. We will study the abundance pattern, trace the plasma density in He-like triplets, enhance the observational findings with accretion shock simulations and relate our results to the long-standing problem of disk dispersal and angular momentum evolution in young stars.

2 Science justification

2.1 Context

Our view on the formation of stars and planetary systems and their emergence from their native molecular clouds has made significant progress over the last decades. For the class of T Tauri stars (TTS), low-mass pre-main sequence stars, X-ray observations have especially helped to shape this view. TTS come in two flavors, the classical T Tauri stars (CTTS) and the weak-lined T Tauri stars (WTTS); both types have been known for a long time to be copious X-ray emitters (Feigelson & Montmerle 1999, ARA&A, 37, 363). Traditionally they were distinguished only by their Hα equivalent width, with those stars of EW $>$ 10 Å defined to be the CTTS. It turned out that the EW of Hα traced to a good part the accretion flow from the circum-stellar disk the CTTS still possess, and that the strength of the line is connected to the mass accretion rate. As discussed in the next section CTTS also differ in their X-ray properties from older main-sequence stars.

2.2 X-ray Observations of CTTS

As a class CTTS stand out from other X-ray sources by their strong soft X-ray excess (Robrade & Schmitt 2007, A&A, 473, 229,Güdel & Telleschi 2007, A&A, 474, L25). In Fig. 1 we show the flux ratio Ne X(Ly$_\alpha$)/Ne IX versus the total Ne flux, and it can be seen that most CTTS are softer than main-sequence stars. But solar-like activity is also present: CTTS exhibit normal coronal activity and stellar flares. The CTTS TW Hya, observed with

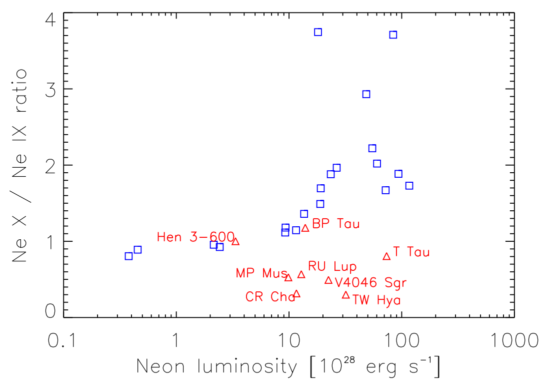

Figure 1: Ratio of the emitted Ne X(Ly$_\alpha$)/Ne IX line flux vs. neon luminosity (Ne IX+Ne X)(Ly$_\alpha$) for main-sequence stars (squares) and CTTS (triangles)

Chandra/HETGS (Kastner et al. 2002, ApJ, 567, 434), exhibits low f/i values in the He-like triplets of Ne IX and O VII (Fig. 2), and this pattern has been found in a number of CTTS. There are exceptions to this rule — in T Tau itself, although known for its high accretion rate, the O VII f/i-ratio is consistent with the coronal limit (Güdel et al. 2007a, A&A, 468, 529). Well studied examples of young MS stars such as AU Mic, Speedy Mic and AB Dor (Ness et al. 2004, A&A, 427, 667) show large f/i ratios similar to older MS objects in the Ne IX and the O VII triplet. Low f/i values originate from high density emission regions (or those with a strong UV field) and this can be naturally linked to accretion (Günther et al. 2007, A&A, 466, 1111).

Observations also reveal abundance anomalies with Ne enhancemet and a depletion of grain-forming elements (Stelzer & Schmitt 2004, A&A, 418, 687;Telleschi et al. 2007, A&A, 468, 443).

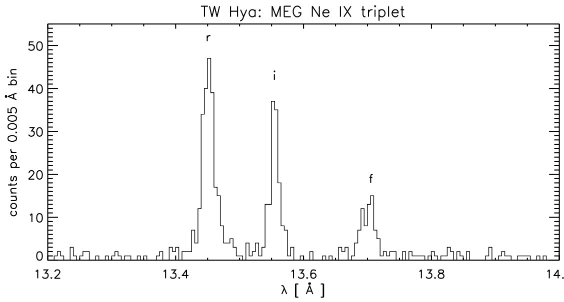

Figure 2: HETGS/MEG spectra in the Ne IX triplet for TW Hya

2.3 Accretion models

The accretion disk does not reach down to the star, but is truncated at a few stellar radii by the stellar magnetic field. Stellar radiation ionizes the inner disk material, which is forced to follow the stellar magnetic field lines to impact onto the stellar surface with free-fall velocity (Koenigl 1991, ApJ, 370, L39; Shu et al. 1994, ApJ, 429, 781). This magnetic interaction between the star and the disk determines how stars build up their masses and transport angular momentum between the two.

The kinetic energy of the infalling gas is released in a standing shock wave, which heats the gas to temperatures of 2-3 MK. This accretion hot spot explains, among other things, the optical veiling of CTTS (Calvet & Gullbring 1998, ApJ, 509, 802), and the soft X-ray component emitted by the cooling post-shock gas (Lamzin 1998, Astronomy Reports, 42, 322). This same picture nicely explains the observed line ratios and allows, through careful fitting, for a reconstruction of the density and velocity of the infalling material (Günther et al., 2007).

The relative importance of the accretion component and the coronal component varies between individual objects. Modelling the accretion spot allows us to disentangle accretion and coronal components. One such example is shown in Fig. 3. Further sources of X-ray emission in CTTS are extended hot jets, spatially resolved by *Chandra* in DG Tau (Güdel et al. 2008, A&A, 478, 797), and possibly a shock at the unresolved jet base. DG Tau is a prime example of a CTTS with a highly absorbed hard component and a much less absorbed soft component (Güdel et al. 2007b, A&A, 468, 515). This makes the accretion spot an unlikely source of the emission from this particular star since this would require similar amounts of absorption as the corona.

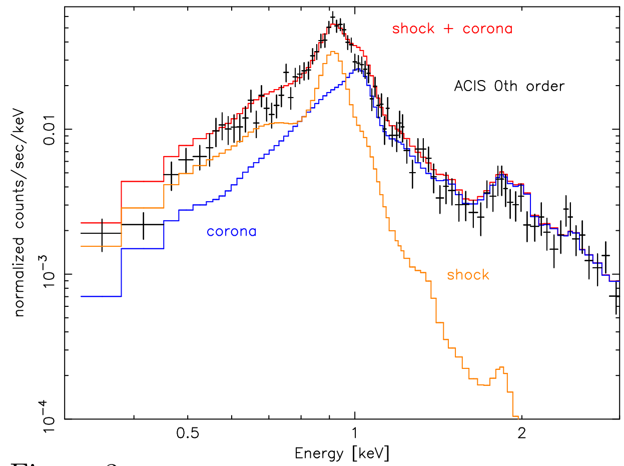

Figure 3: *Chandra* ACIS spectrum of V4046 Sgr, decomposed in coronal and accretion component.

2.4 WTTS

WTTS with their low Hα EW are generally expected not to show accretion. It is intriguing to interpret the WTTS as more evolved CTTS, having lost their disks over time by accretion, coagulation into planetary bodies and photoevaporation. Comparative studies of CTTS and WTTS therefore allow an estimate of the timescale of disk dispersal and give upper limits on time when planets form. Yet, the observational evidence is not as clear as theoreticians would like it to be. For many TTS the Hα EW is known to be variable, and 5 of 83 WTTS observed (Padgett et al. 2006, ApJ, 645, 1283) actually show an IR-excess caused by dust within a few AU from the star, detected by *Spitzer*. Systems containing WTTS like TWA 4 (Kastner et al. 2004, ApJ, 605, L49) and TWA 5 (Argiroffi et al. 2005, A&A, 439, 1149) or young MS stars show no sign of active accretion and no high densities in their X-ray spectra. However, there are a few special cases, where stars appearing as WTTS turned out to have a surprisingly large accretion rate (Littlefair et al. 2004, MNRAS, 347, 937).

2.5 Objective

As outlined above, CTTS are complicated objects, where different emission regions can contribute to the observed X-ray flux. In contrast, WTTS, likely more evolved objects, have simpler X-ray spectra. Only the study of intermediate objects can answer the following important questions:

- When accretion decreases, how does the f/i-ratio evolve? If we find a low f/i and therefore a high density in the accretion region, despite a small accretion rate, than the filling factor is small and we can deduce that only a small number of field lines connects to the disk. If the f/i ratio is compatible with the low-density limit, than the mass loading per field line decreased compared to stronger accretors. Only X-ray observations can help answering this question, because they directly observe density tracers in the accretion shock. The result places important constraints on the angular momentum transfer to the disk.
- When accretion decreases, how long is the cool excess visible? Does it switch off between CTTS and WTTS or do as yet unseen intermediate stages exist? If it switches rapidly, do transition objects like IM Lup appear as CTTS or as WTTS? If no soft component is found, this poses the theoretical problem to find a mechnism which stops accretion from a disk (see Sect. 2.6).
- How does IM Lup compare to TW Hya? TW Hya is also an evolved CTTS with a low accretion rate, low circum-stellar absorption and no jets, which are signatures of young, active objects, yet its Hα EW is more than an order of magnitude higher than in IM Lup.

2.6 IM Lup

We therefore propose to observe an object on the borderline of CTTS and WTTS with the *Chandra*/HETGS to obtain high resolution spectra. We emphasize that *Chandra* is the only instrument available which allows to safely diagnose the Fe XIX contamination in the Ne IX triplet, which is absolutely crucial to measure the density. We will test the observed abundance pattern and fit our shock models (Günther et al., 2007) to the observed data.

Our target, IM Lup, is the only known X-ray bright transition object with a low, but varying Hα EW (7.5-21.5 Å), far less than the value of the prototypical CTTS BP Tau and TW Hya. On the other hand, the IR-excess in IM Lup (Fig. 4) indicates the presence of a disk (Padgett et al., 2006), making it a favorite object for disk evolution studies in the IR (Schegerer et al. 2006, A&A, 456, 535). The disk still has a significant gas content, which is seen as a double-peaked profile in observations of CO emission lines originating in the cooler part of the disk (van Kempen et al. 2007, A&A, 461, 983). At the same time, IM Lup is a strong X-ray source; a CCD spectrum taken with the *XMM-Newton* MOS is shown in Fig. 5. If IM Lup's X-ray flux is coronal, its Ne IX f/i-ratio is expected to

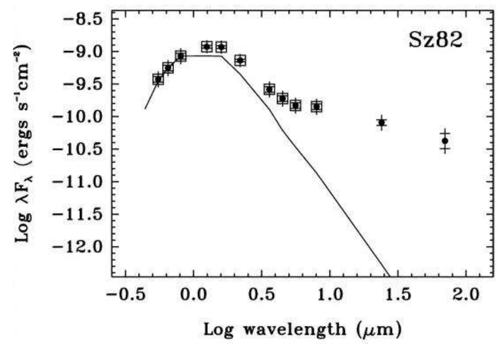

Figure 4: Measurements for IM Lup = Sz 82 and model photosphere. The IR excess can clearly be seen. From: Padgett et al. (2006)

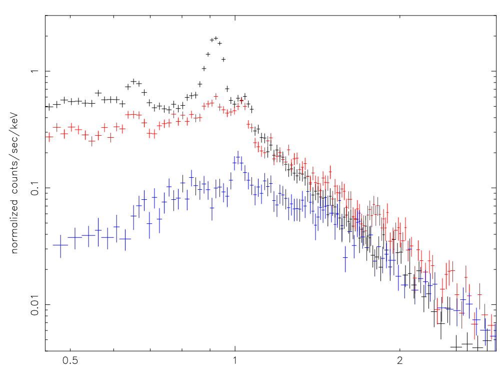

Figure 5: *XMM-Newton* MOS spectra (top to bottom) of TW Hya (black), TWA 5 (red) and IM Lup (blue)

be large; if the X-ray flux is accretion dominated, we expect significant deviation from the low density f/i limit; but in either case it is clear that there is detectable emission in the Ne IX triplet. Furthermore this diagnostic is sensitive to densities that are found in TW Hya, one of the oldest CTTS. Fitting the abundances to the MOS spectrum, there are indications of a CTTS-like iron depletion and a neon enhancement, albeit with large statistical uncertainties. A long *Chandra* exposure will establish abundance anomalies beyond doubt, and provide line fluxes for placing IM Lup as first transition object in the Ne X/Ne IX plot (Fig. 1).

3 Feasibility

To asses the density of the accretion plasma, we need to measure f/i ratios in He-like triplets, but IM Lup's low flux at $\sim$ 600 eV renders observations of the O VII triplet unfeasable (Fig. 5). The observation of the Ne IX triplet requires a high spectral resolution to avoid blending of the Ne IX triplet with Fe XIX lines and a sufficient number of photons, which we calculate below. As long as we meet this goal, the SNR will be high enough for all other mentioned points. A three-temperature fit to the CCD spectrum of IM Lup (Fig. 5) shows more than half of the emission at hot temperatures ($>$ 10 MK). Thus Fe XIX should be seen in the spectrum, and only *Chandra* offers the spectral resolution required to separate these lines from the Ne IX triplet.

Ness et al. (2004) analyze coronal sources and find f/i ratios larger than two for all sample stars, including young active stars. On the contrary, most Ne IX f/i ratios found in CTTS so far are around one (e.g. Günther et al. 2006, A&A, 459, L29, Argiroffi et al. 2007, A&A, 465, L5). To confidently discriminate between these case, we need to be able to distinguish between a ratio of 1 and 2.

The ratio of the r line to the sum of f and i line is moderately temperature sensitive with a value around one. Depending on the density and UV field, photons are redistributed between the f and the i line. We therefore performed a variety of calculations varying the total number of recorded counts in the f and i line. Under the assumption that the true f/i ratio is two, we need at least 30 counts in total in the f and i line to accept or reject the hypothesis of a CTTS-like f/i-ratio in IM Lup at the 90% confidence level. Using XSPEC we ran several simulations with

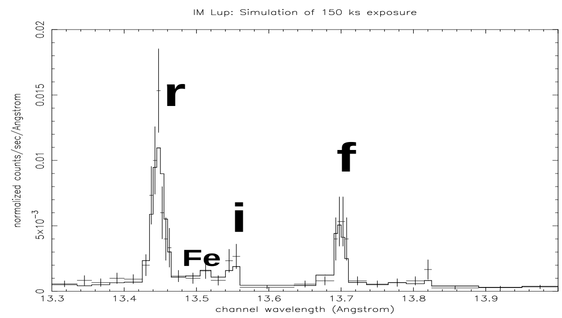

Figure 6: Simulated *Chandra* MEG spectrum in the Ne IX triplet region of IM Lup, exposure time 150 ks, binned to min. 5 cts/bin, in the low density scenario.

the MEG response and our thermal model (see Fig. 6) About 150 ks exposure time are required to obtain at least a total of 30 counts in the sum of the forbidden and intercombination line after adding positive and negative MEG orders. As a consistency check we compare this estimate with the observation of TW Hya. There the observed *XMM-Newton* MOS count rate density at 0.9 keV is about 2 cts/s/keV, in IM Lup one finds 0.1 cts/s/keV; in TW Hya 200 counts (Ne IX f+i) were obtained in a 50 ks observation, therefore in IM Lup we expect roughly 30 counts in 150 ks, consistent with our more detailed estimate above. We remark that we will also be able to test for higher densities in the He-like triplets of Mg XI and Si XIII, where we expect 80 and 50 counts respectively.

In summary, we request a 150 ks *Chandra* HETGS observation of IM Lup to measure the densities in the X-ray emitting regions with the Ne IX triplet. This will provide a crucial test for the evolution of the accretion process in young accreting TTS. IM Lup is the only known X-ray bright object with a confirmed disk that is in transition between CTTS and the MS, where this analysis is feasible. It is a unique *Chandra* project, since the unmatched spectral resolution of the *Chandra* HETGS makes this the only instrumental setup that allows a clear separation of Fe XIX and the Ne IX triplet.

4 Previous Chandra Programs

I did not lead any *Chandra* programs as PI yet, though I have worked extensively with archival data.