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Accretion, fluorescent X-ray emission and flaring magnetic structures in YSOs

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Abstract. I present some recent developments on high-energy phenomena in YSOs, concentrating on the new evidence for accretion-induced X-ray emission in YSOs, for Fe 6.4 keV fluorescent emission from the disks of YSOs and for very long magnetic structures responsible for intense X-ray flares, likely connecting the star and the circumstellar disk.

Key words. Young stars – X-ray emission

1. Introduction

YSOs were identified as copious sources of X-ray emission in the early days of imaging X-ray astronomy, immediately raising a number of long-debated questions. Significant progress has been achieved in the last couple of years on a number of them, thanks to the availability of new observational material. I will discuss here three of these questions.

X-ray emission starts to become present in Class I objects, with no confirmed detection of X-ray emission from Class 0 sources. Class II (CTTS) and Class III (WTTS) objects are almost always detected as strong X-ray sources. The possible difference in the X-ray behavior and in the emission mechanisms between CTTSs (with active, accreting disks) and WTTSs (with no ongoing accretion, and thus less disturbed photospheres) has been an open topic until very recently. In particular the role of accretion has been often debated, but with very little observational evidence. The recent availability of high-resolution X-ray spectra of CTTS is finally allowing to address the issue, and is showing that accretion is indeed causing a part of the X-ray emission observed in CTTS, with much interesting physics going on.

Once it became evident that YSOs are strong and persistent X-ray sources, the question immediately arose how and to which extent they affect the circumstellar environment, and in particular the accretion disk and its proto-planetary environment. The details of the geometry (e.g. the relative position of the X-ray sources and of the disk material, the degree to which the X-rays penetrate the disk, which depends on the angle of incidence, etc.) are critical, but direct evidence for the amount of interaction between stellar X-rays and the disk has only been available recently, thanks to the *Chandra* and XMM-*Newton* observations of fluorescent X-rays from the disks of YSOs.

The geometry of the magnetic field on and around YSOs has also been a topic of debate. Photospheric fields have been measured, and range into the kG domain, but how these ex-

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tend further from the stellar surface, and how do they link to the disk structure, is not obvious. The magnetospheric model of accretion postulates flux tubes connecting the disk's inner boundary and the photosphere, but whether such structures are also the seat of coronal plasma is not known. The evidence available to date using the analysis of flare decay on older stars invariably points to compact coronal structures, extending at most a fraction of the stellar radius from the photosphere. New long X-ray observations of a large number of YSOs in the ONC (the COUP project, presented elsewhere in this book) have allowed to extend this type of analysis to YSOs.

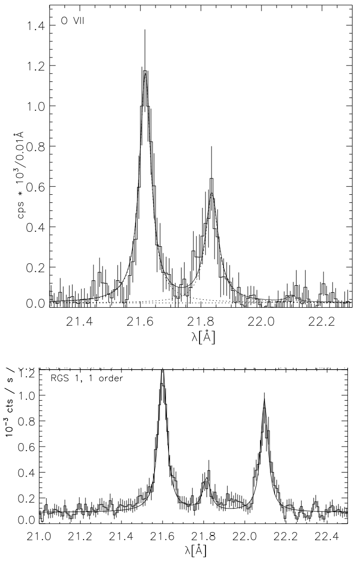

Fig. 1. The O VII triplet in TW Hya as observed by XMM-*Newton*, compared with the same spectral region observed in a normal coronal source (YY Gem, bottom panel). The absence of the forbidden line in TW Hya is evident. Figure courtesy of B. Stelzer.

2. Accretion and X-ray emission

The generally accepted model for accretion from the disk into YSOs (the magnetospheric model) envisions plasma being channeled into magnetic flux tubes and ramming onto the star at essentially free-fall speed. For normal YSO parameters (mass and radius) this implies shock temperatures of up to a few MK, and thus possible shock-related X-ray emission. However, the X-ray emission from the majority of CTTS is dominated by much hotter plasma (up to some tens of MK), which cannot be directly produced by accretion shocks. The first *Chandra* high-resolution spectra of a CTTS, TW Hya, therefore came as somewhat of a surprise, in that its density-sensitive O VII He-like triplet (as well as the Ne triplet) show very low values of the ratio between the forbidden and intercombination lines ($R = f/i$) (Kastner et al. 2002), a result confirmed by the XMM-*Newton* observation (Stelzer & Schmitt 2004). R is a density-sensitive line ratio, and the low values observed in TW Hya are compatible with very high coronal densities, $n_e \simeq 10^{13}$ cm^{-3} for the plasma at temperatures 1–3 MK (at which the O VII triplet is formed). Such densities are never observed in older active stars, where the O VII R ratio typically implies densities of at most a few times 10^{11} cm^{-3}.

TW Hya is also peculiar in its low-resolution X-ray spectrum, which shows no significant amounts of plasma hotter than $\simeq 3$ MK, so that the bulk of TW Hya's X-ray emission is compatible with being produced in an accretion shock. But, while high densities are expected in a shock, they are not the only possible cause of low O VII triplet R values: high UV fluxes can radiatively depopulate the atomic level associated with the f line and thus result in low R independently from the density (low R values are in fact normally observed in early type stars, where the UV pumping is clearly the cause). While Kastner et al. (2002) and Stelzer & Schmitt (2004) both interpreted the observed R value as due to high density, Drake (2005) has shown that this interpretation has a problem: due to the density structure of the shock, to reach $n_e = 10^{13}$ cm^{-3} in the X-ray emitting region the shock should be buried below such a high column density of material as to totally absorb the emitted (soft) X-rays. On the other hand, if indeed the X-ray emission is shock-emitted, its association with the accretion hot spot (which has typical temperatures of 8000–10 000 K) would embed the X-ray emitting plasma in a strong UV flux, which would induce a low R value. As the two effects cannot be distinguished, the actual density of the plasma cannot be determined directly; nevertheless, given the very small filling factor ($f \simeq 1\%$) of the accreting spot, to be affected by the UV flux the plasma must be located very close to the accretion spot. Therefore, *independently from the relative contribution of UV flux and high density*, the low observed R value points to a strict association between the accretion spot and the X-ray emission.

TW Hya has been until very recently the only CTTS observed in X-rays at high spectral resolution, raising the question of whether the low R ratios and therefore the associated physics are a common phenomenology in CTTS or whether TW Hya itself is a peculiar object. Another CTTS, BP Tau, has been observed at high resolution during the summer by XMM-*Newton*, and the result (Schmitt et al. 2005) is that also in BP Tau the O VII R ratio is very low, again pointing at a close association between the 1–3 MK plasma and the accretion spot. However, unlikely TW Hya, BP Tau has significant amounts of hotter plasma, up to $\simeq$ 30 MK, which cannot be produced in the accretion spot, as not enough gravitational energy is available. The hotter plasma must then be produced in some form of coronal process, i.e. from magnetically confined – and heated – plasma. The magnetic confinement in other CTTS is made evident by the presence of flares with a decay typical of flares in older stars, and implying confinement. Therefore, it appears that, in CTTS, both accretion produced X-ray and coronal X-rays can coexist, and that production of significant soft X-ray flux in the accretion shock in YSOs possibly is a common, general phenomenon. As discussed in Sect. 4, the magnetic structures responsible for the confinement of the hotter plasma, may also be confining the accreting material.

3. X-ray fluorescence in accretion disks around YSOs

The material in the accretion disk in a YSO will be exposed to stellar X-rays (whether coronal or accretion produced); exposure to high-energy radiation has in fact been invoked as the mechanism explaining e.g. the isotopic anomalies observed in some types of meteorites, as well as the recent detection of calcite around some YSOs (Chiavassa 2004); in terrestrial condition the formation of calcite requires liquid water, and it is therefore difficult to picture how calcite could form in the cold conditions of an accretion disk; temporary thawing in ice particles induced by absorption of energetic photons could however lead to calcite formation (Chiavassa 2004).

Until recently, the evidence for the interaction of stellar X-rays with the circumstellar material has been indirect. Direct evidence for interaction of X-rays with disk material is now present in the form of detection of fluorescent X-ray emission from “cold” material. The X-ray spectrum of hot plasma ($T \geq 30$ MK) is characterized by emission from a complex of lines around 6.7 keV, originating from Fe XVV, which is typically very evident (as an unresolved line) in low resolution X-ray spectra of YSOs. If cold material ($T < 1$ MK) is irradiated with energetic X-rays ($E \geq 7.11$ keV), neutral Fe will be photoexcited, and will produce X-rays in a number of lines centered at around 6.4 keV. The equivalent width of the 6.4 keV line (also unresolved in low-resolution spectra) depends on a number of factors, such as the intensity and spectrum of the incident radiation, the fluorescent efficiency, and the amount of fluorescing material and its geometry.

Fluorescent Fe emission at 6.4 keV was first detected during an intense flare in a Class I source in ρ Oph (YLW 16A) by Imanishi et al. (2001), and recently the same phenomenon has been observed in a number of YSOs in the ONC (Tsujimoto et al. 2005), using the very long COUP *Chandra* observation. In all these cases, the fluorescent emission was associated with intense flares, which produced the high-energy photons needed to excite the fluorescent emission. The low quiescent X-ray flux from the ONC sources (given their distance) does not allow to determine if the fluorescent X-ray emission is only associated with intense flares (and thus is a sporadic, transient phenomenon) or whether is a persistent feature in these stars.

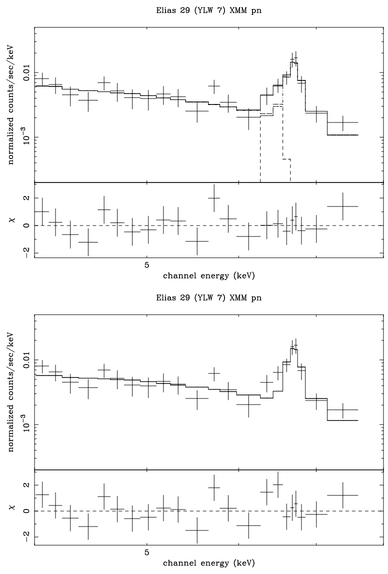

Fig. 2. The XMM-*Newton* EPIC pn spectrum of Elias 29 (from Favata et al. 2005a). The bottom panel shows the best-fit spectrum assuming emission from a hot plasma, the top panel shows the additional 6.4 keV fluorescent line from "cold" Fe needed to ensure a good fit to the data.

Also very recently, a study of the *Chandra* and XMM-*Newton* observations of another Class I source in ρ Oph, Elias 29 (Favata et al. 2005a), has shown intense Fe 6.4 keV fluorescent line emission both during the quiescent phases of its coronal emission and during a moderate intensity flare.

The equivalent width of the 6.4 keV emission observed in Elias 29 is large ($\simeq$ 140 eV, Favata et al. 2005a). This is a powerful diagnostic of the geometry of the fluorescing material; values $\geq$ 100 eV exclude, given the spectrum of the coronal X-ray emission from the star (from which the photons exciting the fluorescence are coming) that the emission can come from diffuse, homogeneous circumstellar material. It also allows to exclude that the fluorescence is due to reflection from either a photosphere or a circumstellar disk illuminated from above. In fact, equivalent widths $\geq$ 100 eV can only be produced (George & Fabian 1991) by a disk illuminated by a source placed in a central hole. In addition, the disk must be seen "face on", as the equivalent width rapidly decreases with disk inclination. In the case of Elias 29, the low inclination of the disk axis relative to the line of sight has been independently derived based on the IR spectrum (Boogert et al. 2002). The centrally illuminated disk geometry is perfectly compatible with a YSO system, in which the X-ray source is located close to the star, and therefore only illuminates the disk from inside the central gap. This excludes more exotic geometries, such as coronal loops located solely on the accretion disk, but it's compatible with the type of loops interconnecting the star and the disk discussed in Sect. 4.

The face-on orientation is the statistically least probable one, so that it's likely that Fe 6.4 keV fluorescent emission is a common occurrence among YSOs, but that only a small fraction of them will result in an observable line in the spectrum, due to the inclination constraints. As the conditions in the disk are optically thick with respect to the X-ray energies involved (the derivation of the equivalent width by George & Fabian 1991 is the result of a full radiation transfer treatment), the observation of the Fe 6.4 keV fluorescence line provides a quantitative measure of the influence of the stellar X-ray emission onto the circumstellar disk, a necessary input to e.g. understand its effect on the disk chemistry. A number of deep X-ray observation campaigns are ongoing or recently proposed, which will hopefully lead to additional detection of objects like Elias 29.

4. Size of flarings structures

The analysis of the decay of powerful stellar X-ray flares allows to determine the size of the flaring structure, and therefore to derive a number of important quantities, such as the density of the flaring plasma and the strength of the confining magnetic field. In the last years, a number of well-resolved flares have been studied on older active stars (see Favata & Micela 2003 for a review), invariably resulting in relatively compact flaring structures, smaller than the star itself. The COUP sample allows for

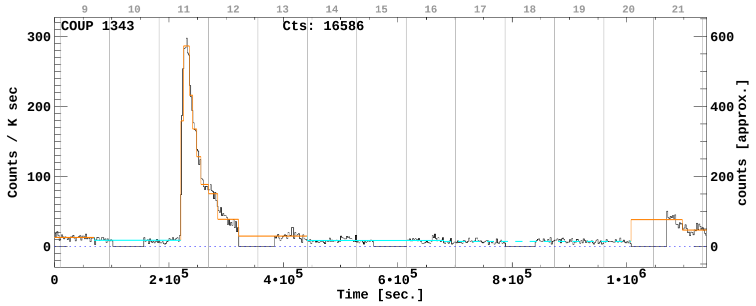

Fig. 3. The intense X-ray flaring event observed by the *Chandra* ACIS instrument in the ONC star COUP source 1343.

the first time to extend this analysis to a significant number of YSOs, with a number of large flares present in the data set. Some 30 events have sufficient statistics to allow a detailed study, and their analysis (Favata et al. 2005b) reveals a broad range of physical parameters for the flaring structures. The most notable result is that in some cases the size of the flaring structure turns out to be much larger than observed in older stars. One excellent example is the flare shown in Fig. 3: at its peak the flare outshines the quiescent emission by a factor of $\simeq 30\times$, and the flare lasts for more than two days. The observed peak temperature is well above 100 MK (the precise value cannot be determined due to the the characteristics of the *Chandra* ACIS spectrometer, whose spectral range only allows to put a lower limit to temperature ≥ 100 MK), and it decays rapidly, allowing to constrain the presence of sustained heating during the decay. The long $1/e$ decay time, $\tau = 40$ ks, can only be explained by the decay of a very long magnetically confined flaring loop, with a semi-length $L \simeq 10^{12}$ cm. Shorter flaring loops would decay more rapidly, due to the combined influence of higher density (and thus higher emissivity) and larger conductive losses toward the chromosphere. The resulting plasma density is $n_e \simeq 2 \times 10^{10}$ cm^{-3}, and the minimum magnetic field necessary to confine the plasma at the maximum temperature is 150 G. Source 1343 in the COUP sample is the best example of a very long flaring structure, but by no means the only one, so that these structures appear not to be exceptional in YSOs.

Such large coronal structures are not at all similar to the ones seen in older stars, which typically have $L < R_*$. While no radius determinations are available for COUP source 1343, assuming the typical radius at this age for a low-mass star of a few solar radii, one finds $L \simeq 10R_*$. The size of the flaring loop thus is a non-negligible fraction of an AU ($L \simeq 0.1$ AU), so that the flaring structure extends (together with the associated magnetic field) significantly in what would be considered “circumstellar space”.

Whether these large magnetic structures containing hot plasma actually link the star with the circumstellar disk cannot be established directly, but it certainly is a possibility. In fact, given that solar, and by extension stellar, coronae appear to be heated by flux braiding at the footpoints of the loops, it’s very likely that the flux tubes responsible for the magnetospheric accretion, would also be subject to the same process (with plenty of flux shear also available to the footpoints anchored onto the disk), so that the falling plasma could be heated by magnetic processes. In fact, detailed modeling of UV excesses from YSOs shows that the plasma in the flux tube channeling the accretion flow is likely heated, producing an UV excess above the one produced by the accretion spot.

5. Conclusions

Magnetically confined plasmas and the attendant high-energy processes are a common feature of YSOs, which plays an essential role in e.g. affecting chemical processes in the circumstellar disk. As discussed above, the recent detection of X-ray fluorescence from circumstellar disks shows that indeed this is likely to be a common process, and provides a quantitative basis for the modeling of the chemical effects of high energy radiation. In addition, the detection of very long (up to $\simeq$ 0.1 AU) flaring structure on YSOs (an unique feature, not present among older active stars) shows that magnetic activity may influence accretion, if the long flux tubes in which the flares are taking place are indeed the same which channel the accretion flow.

High-energy processes are therefore not a "minor constituent" of star formation, but rather one essential element, with broad reaching implications. And, we are just beginning to unravel some very interesting pieces of the puzzle.

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