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What can X-rays tell us about accretion, mass loss, and magnetic fields in young stars?

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Abstract. Until recently, X-rays from low-mass young stars ($10^5 - 10^6$ yr) were thought to be a proxy for magnetic activity, enhanced by 3-4 orders of magnitude with respect to the Sun, but otherwise similar in nature to all low-mass, late-type convective stars (including the Sun). However, there is now increasing evidence that specific X-ray emission mechanisms are at work when the young stars are still accreting from their circumstellar disk. The most frequently invoked mechanism is accretion shocks along magnetic field lines ("magnetic accretion"). In the case of the more massive A and B stars, and their progenitors the Herbig AeBe stars, other, possibly more exotic mechanisms can operate: star-disk magnetic reconnection, magnetically channeled shocked winds, etc. In any case, magnetic fields, both on small scale (surface activity) and on large scale (dipolar magnetospheres), play a distinctive role in the emission of X-rays by young stars, probably throughout the IMF.

Key words. Protostars, T Tauri stars, Herbig stars, Ap-Bp stars, OBA stars, accretion, mass-loss, radiative winds, jets, shocks, magnetic fields

1. Introduction: early stellar evolution and magnetic fields

Young stars, i.e., with ages of a few million years, are now known to form and evolve via a combination of *mass accretion* and *mass loss*, although this combination takes different forms depending on the final mass of the stars. While the way in which massive, hot stars (typically O and B stars, i.e., $M_\star \sim$ a few $M_\odot$ to $M_\star \sim$ a few $10 M_\odot$) form is still debated (e.g. Beuther et al. 2007), it is clear that (except perhaps at the very early stages) they do not possess circumstellar accretion disks, but that they lose mass, in the course of their evolution, via powerful radiative winds ($\dot{M} \sim 10^{-6} - 10^{-5}$ $M_\odot$ yr^{-1}). In contrast, as illustrated in Fig. 1, low-mass stars, and in particular solar-like stars, form as a result of the collapse of an extended protostellar envelope, via the formation of an embedded accretion disk. Such disks live for a few million years, throughout the so-called "classical T Tauri" (CTTS) phase (e.g., Hillenbrand 2006). In the early phases, mass loss is observed to take place in the form of bipolar jets and outflows: this is sometimes called the "accretion-ejection" phenomenon. Although there are significant differences in the proposed theoretical models, it is widely accepted that accretion and ejection are closely coupled via *magnetic fields*, at least out to spatial scales of a few stellar radii, and perhaps even (in some models) throughout the accretion disk ("disk winds") (e.g., Pudritz et al. 2007). Basically, while matter accretes onto the central star as a result of gravitation and viscous dissipation in the disk, owing to the centrifugal force part of the inward-moving material is flung away along magnetic field lines. Interestingly, the observed mass-loss rates in jets are comparable to those in massive stars, and the ratio between mass-loss and accretion is measured to be $\sim 10 - 30\%$. Indirect evidence for winds from the inner disk can be obtained via modeling of the Hα emission of CTTS (Kurosawa et al. 2006).

In contrast, magnetic fields are not thought to play a major role in the early evolution of massive stars, but as discussed below, there is now evidence for their presence, also on large spatial scales, in a significant fraction of O and B stars, and for their influence on the radiative winds. The situation of intermediate-mass stars (the so-called "Herbig AeBe" stars, with $M_\star \sim 2 - 4 M_\odot$), is less clear, but in a few cases there is also similar indirect evidence for large-scale magnetic fields.

Direct measurements and modeling of magnetic fields have made spectacular advances in recent years, thanks mainly to observations of the Zeeman effect via spectropolarimetic measurements and Doppler imaging techniques (e.g., Donati et al. 2007, Strassmeier & Rice 2006, Yang et al. 2007). However, indirect access to magnetic fields has been provided for a long time by X-ray observations (spectra, timing), based on the idea that the only way to confine a hot plasma ($T \sim 10^6 - 10^7$ K, i.e., thermal X-ray energies $\sim$ 0.1 to a few keV) is to trap it in magnetic loops (e.g., Feigelson & Montmerle 1999, Güdel 2004, Micela & Favata 2005). The numbers obtained by the various methods for the surface magnetic field intensities are quite similar: $B_\star \approx 0.1 - 1$ kG, i.e., comparable to values obtained in present-day solar active regions.

The strong connection between X-ray emission and magnetic fields in young stars is the point we want to make in this paper. Sect. 2 presents a brief review of X-ray emission processes in young stars, followed by their application to low- and intermediate-mass stars (Sect. 3), and OB stars (Sect. 4). Recent X-ray evidence for "magnetospheric accretion" in young low-mass stars will be summarized in Sect. 5, while the possible X-ray connection between intermediate-mass and massive stars will be made in Sect. 6. Less common X-ray emission mechanisms will be presented in Sect. 7, and conclusions will be given in Sect. 8.

2. X-ray emission from young stars: processes and environments

2.1. Links with internal and photospheric structure

Stellar X-rays are thermal in the ~ keV range, and can be produced as the end result of internal structure processes. This is the case for low-mass stars, which have outer convective envelopes. Magnetic fields are currently thought to be generated via the dynamo effect at the bottom of the convective zone (the "tachocline", in solar parlance)(e.g., Brun & Zahn 2006), and to buoy out to the surface across the convective zone. Reconnections between magnetic loops of opposite polarity, anchored in the photosphere, result in flaring and sudden heating of the photospheric gas to X-ray temperatures. The heating is provided by fast electrons accelerated by non-thermal, MHD processes, taking place during reconnection (Tanuma & Shibata 2005; see also Güdel, this conference). The almost fully ionized hot gas (plasma) subsequently cools, usually within a few hours, resulting in a decay of the X-ray emission. Re-heating can occur in the process (Reale et al. 2004). The prototype of this behavior is the Sun itself, as observed in particular by the *Yohkoh* satellite (Peres et al. 2004), hence the expression "solar paradigm" sometimes used to interpret the X-ray emission from young low-mass stars.

The X-ray signatures of this stellar "magnetic activity" are: *temporal variability* over a time scale of a few hours (flares: fast rise followed by slow decay); frequent 2-temperature spectra, with a *dominant hard component* ($T \sim$ a few 10 MK), and a less important soft component ($T \sim$ a few MK); *"coronal"* plasma densities ($n_e \sim 10^{10} - 10^{11}$ cm^{-3}) (e.g., Wolk et al. 2005). This signature is ubiquitous in all late-type stars; the main difference between

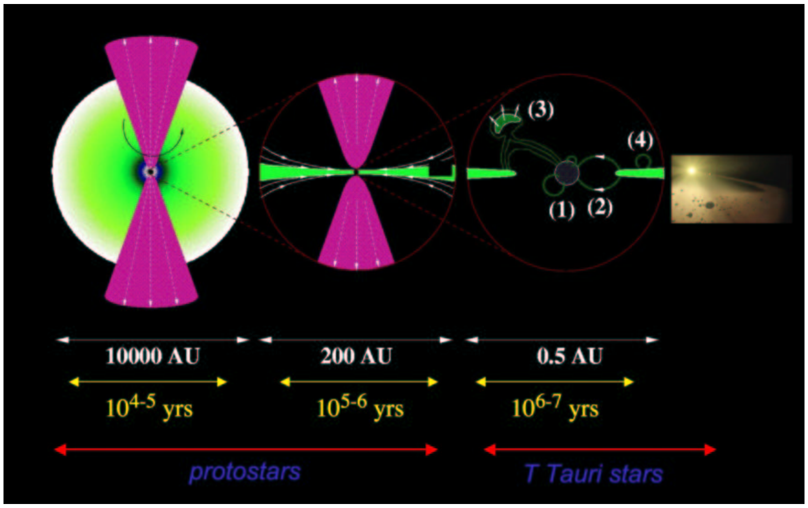

Fig. 1. A brief history of low-mass star evolution, from the protostar stage (*left*) to the planet formation stage (*right*). The "accretion-ejection" phenomenon is characteristic of the protostar stage, while magnetic star-disk interactions are present throughout the evolution. However, they produce X-rays only if the magnetic loops reconnect, resulting in flares, either on the star itself (convection-driven magnetic activity), or between the star and the disk. Size scales and time scales of evolution are indicated. (Adapted from Feigelson & Montmerle 1999)

stellar classes is the level of X-ray luminosity (expressed in L_X/L_{bol}): it is 3-4 orders of magnitude higher than in the Sun, in fast rotating stars (like RS CVn binaries) or in fully convective stars (like dMe stars), and also in T Tauri stars (TTS), which may have both properties.

Stellar X-rays can also be produced by *shocks* at the photospheric level. This is the case of the winds of massive stars, which have been known for a long time to be radiatively unstable (Lucy 1982). In this picture, the winds are sustained by the radiative forces on heavy elements, themselves dragging H and He by atomic collisions. As the wind flows, the Doppler effect shifts the radiation-sensitive transitions, so that the radiative force becomes less efficient: regions close to the stellar surface are more accelerated than distant ones, creating a Kelvin-Helmhotz-like instability. Myriads of shock waves, with velocities ~ several 100 km.s^{-1}, thus criss-cross the wind and emit X-rays (e.g., Kudritzki & Puls 2000)

The X-ray signatures of radiative winds are: *no (or small but random) temporal variability* over time scales of hours; taking into account that, for a constant velocity, the wind density decreases as r^{-2}, so the inner layers are more opaque to X-rays than outer ones, and that shocks are faster there, the net result is that the overall spectrum is dominated by the outer layers: consequently, the spectrum is basically *soft* (sub-keV, or equivalent T ~ a few MK), and the plasma densities are comparatively *low* ($n_e \sim 10^9 - 10^{11}$ cm^{-3}) (see, e.g., Owocki & Cohen 1999).

As explained below (Sect. 4), when a magnetic field exists and is sufficiently strong to confine the wind within a large-scale closed magnetosphere, the signature is modified, the most important change being the possibility of *rotational modulation* of the X-ray emission, at the rotation period of the star.

2.2. Interactions with large-scale or external structures

Since young stars are in general still surrounded by dense material, additional X-ray emission mechanisms are possible, depending on the nature of the interactions between the star and the surrounding medium.

The now classical general picture of young low-mass stars is that of a central star surrounded by a large-scale magnetospheric structure, linking the star and the disk at the corotation radius R_c (typically $R_c \sim 2 - 3R_\star \approx 0.05$ AU). Beyond R_c, the disk is in Keplerian rotation. It is important to realize that the existence of such a magnetosphere is *postulated* in the "accretion-election" paradigm explaining the bipolar jets; *a priori* it has nothing to do with the stellar magnetic field generated by the convective dynamo.

This opens two new possibilities for X-ray emission: (i) *magnetic interactions* between the star and its circumstellar disk, which will be the topic of Sect. 5 and 7; (ii) *shock interactions* between the jet and the surrounding medium (protostellar envelope close to the star, and/or ambient ISM farther away), discussed in Sect. 7. Fig. 2 summarizes the various X-ray emission regions associated with low- and intermediate-mass stars.

3. Low-mass stars: magnetic activity

The X-ray emission from TTS (both "classical", still surrounded by disks, and "weak-line", without disks), is extremely well documented, after over 25 years of X-ray observations of star-forming regions. On the one hand, to date many star-forming regions have been observed by various X-ray satellites, with typical "short" exposures of 30-150 ksec, yielding hundreds of individual T Tauri detections down to the brown dwarf regime. On the other hand, the unique, very long *Chandra* exposure (850 ksec) of the Orion Nebula Cluster (the so-called "Chandra Orion Ultradeep Project", or COUP; PI E. Feigelson), has yielded in a single observation over 1500 detections of TTS (to which are added detections of massive stars and protostars, see below) over a $17' \times 17'$ FOV (Getman et al. 2005). The sub-arcsec angular resolution of *Chandra* allowed a clear spatial separation of the sources, and thus a clean statistical analysis of their X-ray emission properties, sorted according to various parameters: mass, luminosity, rotation (period and/or $v\sin i$), effective temperature, etc. These are reviewed by T. Preibisch (this conference). Another important observation is the "XMM-Newton extended survey of Taurus" (XEST; PI M. Güdel), a medium exposure ($\sim$ 30 ksec/field), medium angular resolution (a few arcsec), but large spatial extension (17 XMM fields, i.e., a total of $\sim$ 5 square degrees) of the Taurus clouds, yielding over 2400 identifications (mostly $2MASS$), of which only $\sim$ 160 are characterized to date as young stars (Güdel et al. 2006a).

For our purpose here, I briefly comment on three main global results from these satellite observations.

• *"Class I" protostars*. Evolved protostars (the so-called "Class I" protostars) are still embedded in their original envelope but near the end of the accretion phase, so that the envelope has become tenuous and absorbs X-rays relatively weakly (N_H up to $\sim 10^{22}$ cm^{-2}, or equivalently $A_V \sim 5$, see Vuong et al. 2003). These protostars are now routinely detected, although their average detection rate is only moderately high ($\sim 40 - 60\%$). This can be explained, at least in part, by extinction effects along the line of sight, reducing the effective sensitivity for a given exposure. Their X-ray emission is basically similar to that of TTS (flaring activity, hard spectra -although the extinction generally prohibits detecting a possible soft component), although more active. It has been suggested that this enhanced activity could be the result of star-disk interactions (Preibisch 2004). We will return to this question in Sect. 7. In any case, this demonstrates that Class I protostars comprise an already mature star in their centers, and basically share the same X-ray properties as TTS.

• *"Class 0" Protostars*. Young protostars (so-called "Class 0" protostars) are at a stage preceding the Class I stage: they are in their main accretion phase, in which matter falls freely on a growing, but still embryonic, star (e.g., Belloche et al. 2006). So far, in most star-forming regions where they exist, no Class 0 protostar has been detected in X-rays (e.g., Giardini et al. 2007). Recently, one positive detection has been reported in R CrA

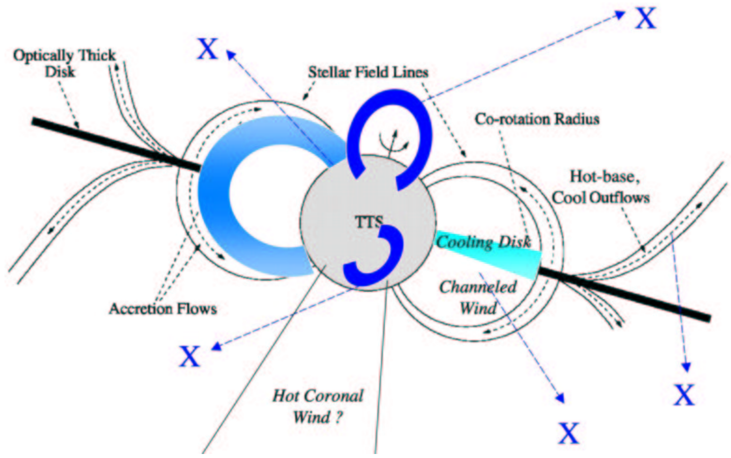

Fig. 2. The various X-ray emission regions that may exist in the environment of low- and intermediate-mass stars: magnetic reconnections (on the star or between the star and the disk), and shocks (magnetically channeled winds, accretion on the stellar surface, outflow collisions with the envelope and/or with the interstellar medium, etc.). (Adapted from Stassun 2001)

(Hamaguchi et al. 2006), but the exact status of the source is unclear; it probably belongs to the so called "Class 0/I", i.e., the transition between the "young" and "evolved" protostars, when the envelope starts to be X-ray transparent, and at the same time the formation of a star at the center is essentially completed. Given the high extinction of Class 0 envelopes (N_H up to several 10^{23} cm^{-2}, i.e., up to $A_V \sim 500$, or more), the present upper limits on their X-ray luminosity are typically higher than for the most luminous T Tauri stars. Therefore it is currently impossible to determine whether the absence of X-rays from Class 0 protostars is real or not, and in particular whether the stellar embryo is magnetized; this situation is likely to hold until the next generation of X-ray satellites

• *T Tauri stars*. There has been a long-standing debate in the literature about whether there was a statistically meaningful difference in X-rays (luminosities, spectra, etc.) between "classical" and "weak" TTS. The question arose originally simply because the additional extinction of the disk of CTTS (if seen more or less edge-on) would *a priori* make their spectra harder and their luminosities smaller, and this effect was not seen. On the other hand, we now know that there are in fact *three* classes of TTS: (i) *accreting* TTS, which have both evidence for the presence of a disk (mostly from near-IR excess), and for accretion (enhanced Hα, CaII, etc., emission: the usual CTTS criterion; see also Sect. 5); (ii) *non-accreting*, more evolved TTS, which still have a disk but no evidence for accretion (hereafter "DTTS", for "disk" TTS; unofficial designation !); (iii) even more evolved *diskless* TTS, which are equivalent to "weak" TTS (evidence neither for a disk nor for accretion). As a result, comparing CTTS and WTTS implies in reality making a distinction between DTTS and "pure" WTTS, and is not the same as comparing the IR-classified "Class II" sources (= CTTS + DTTS) and "Class III" sources (= WTTS).

With the increased sensitivity (i.e., larger sample, lower mass limits, etc.) of the COUP observations, and using only CTTS defined by accretion-related criteria (Hα, CaII), Preibisch et al. (2005) found a statistically significant difference of a factor $\sim$ 2 in X-ray luminosity between CTTS and WTTS, while for instance

Ozawa et al. (2005) found no difference between Class II and Class III young low-mass stars in the ρ Oph cloud core. While, as originally expected, the CTTS turned out to be statistically less X-ray luminous than WTTS, this property was found to be uncorrelated with the disk orientation, pointing to a difference in properties linked with the accretion phenomenon itself, and not to the extinction by disk material. We shall discuss this situation in more detail in Sect. 5.

4. The case of massive (OBA) stars

As summarized above (Sect. 2), massive stars (here understood as stars of spectral types earlier than F), have radiatively-driven winds, which become stronger and stronger as the effective temperature T_{eff} increases. A-type stars ($T_{eff} \sim 7,500-10,000$ K) are fully radiative. They mark the internal structure boundary between later-type, less massive stars (including the Sun), which have a radiative core surrounded by an increasingly extended envelope as T_{eff} decreases, and earlier, more massive stars, which have a convective core surrounded by a radiative envelope, itself increasingly extended as T_{eff} increases. In the extreme, pre-supernova case of the Wolf-Rayet stars, the winds become so strong (up to $\dot{M}_w \sim 10^{-5} M_\odot$ yr^{-1}, $\mathrm{v_w} \sim 1000 - 3000$ km s^{-1}) (e.g., Nugis & Lamers 2000), that the convective core itself becomes exposed at the base of the wind. In any case, for A stars and earlier types, no outer, convectively-driven magnetic fields are expected.

Yet, we know that a significant fraction of the A and late B stars ($\sim$ 5%, see Wade 2005), the so-called Ap and Bp stars, characterized by huge overabundances of heavy elements, are magnetic, with magnetic field strengths $B_\star$ reaching several kG (the record being held by Babcock's star, HD 215441, with $B_\star \sim 11.5$ kG). The interpretation of overabundances is in terms of element diffusion driven outwards by radiation pressure, but accumulating in the upper photosphere because they are trapped by the magnetic field. Modeling of this effect, together with spectral time variability and/or Doppler imaging, has led to a picture in which the Ap and Bp stars are surrounded by a dipolar, or sometimes multipolar, magnetosphere several stellar radii in size (Michaud 2004). Also, nonthermal radio emission has been detected from a number of O and B stars, and modeled in terms of gyrosynchrotron emission from mildly relativistic electrons trapped in a large magnetosphere (André et al. 1988, Trigilio et al. 2004). The widely accepted interpretation is that of fossil fields brought from the ISM during the early formation and evolutionary stages, but surviving under special, unknown circumstances, although recent work suggest the possibility of an internal, non-convective origin (see MacDonald & Mullan 2004, and refs. therein).

On the other hand, X-ray observations have shown that O and B stars obey a simple correlation: $L_X/L_{bol} \sim 10^{-7}$, over a wide range of luminosities (Berghöfer et al. 1997). This correlation has been nicely explained by Owocki and Cohen (1999), in terms of a rather delicate balance between the X-ray emissivity of shocks in the radiatively unstable winds, and extinction as a function of depth in the wind. However, for A stars the calculated radiative winds are very weak ($\dot{M}_w \sim 10^{-10} M_\odot$ yr^{-1}, e.g., Babel & Montmerle 1997a), and in fact undetectable, and these stars do not have outer convective zones. Yet many normal A stars (and their predecessors the Herbig AeBe stars) are seen to emit X-rays, in contradiction with expectations. However, the case seems now settled: at least in the ONC, the COUP observations have shown, for the 50% detected A stars, that they are highly variable, and that their temporal behavior (flarelike light curves, time scales, duty cycle, etc.) are statistically indistinguishable from that of TTS (Stelzer et al. 2005). This confirms the longtime suspicion that the X-ray emission from A stars is actually coming from a magnetically active, unresolved low-mass companion. The case of the Herbig AeBe stars is less simple, and will be discussed in Sect. 6.

Returning to the X-ray emission of massive stars, the COUP observations of a sample of 9 O7 to B3 stars in the vicinity of the Trapezium (the "strong wind" sample of Stelzer et al. 2005) have also shown a signif-

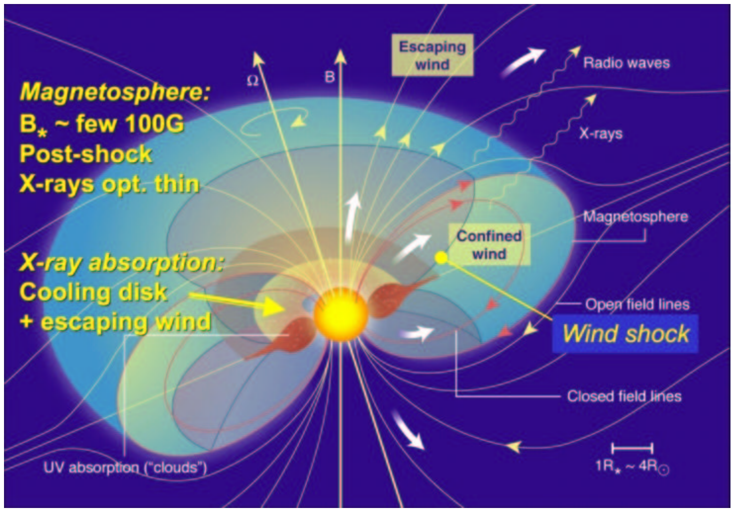

Fig. 3. The "magnetically channeled wind shock" (MCWS) model, initially proposed by Babel & Montmerle (1997b) to explain the X-ray rotational modulation of θ^1 Ori C. In this model, the radiatively-driven wind of a hot star (O, B, or A star) is confined by a strong magnetic field, and "self-collides" along the equator, heating the post-shock gas to X-ray energies. Then the shocked wind cools in a dense disk. This disk, in turn, absorbs the X-rays, and if the viewing geometry is favorable, causes a rotational modulation of the X-ray flux. (Adapted from Montmerle 2001)

icant excess of X-ray emission over the nominal $L_X/L_{bol} \sim 10^{-7}$ correlation in three stars, as well as three cases of X-ray rotational modulation in the whole sample. The most spectacular case is that of θ^1 Ori C, the most massive star (O7, $M_\star \sim 45\ M_\odot$) of the Trapezium cluster. The COUP observation confirmed (with much better statistics) the earlier *ROSAT* result of X-ray modulation (Gagné et al. 1997), with an amplitude of a factor ~ 2, at the rotation period of the star ($P_{rot} = 15.4d$). To explain both the high X-ray luminosity of θ^1 Ori C ($L_X/L_{bol} \sim 10^{-5}$), and its rotational modulation, Babel & Montmerle (1997b: BM97) proposed a new model of X-ray emission from O stars. This model was based on an earlier model devised for the Ap star IQ Aur (Babel & Montmerle 1997a), in which the (known) strong dipolar magnetic field could confine the weak (unknown but computed) radiative wind, and channel it along both hemispheres into an equatorial shock. At this shock X-rays are generated, and absorbed by an equatorial disk formed by the cool, post-shock material.

In the case of θ^1 Ori C, the wind properties (velocity, mass-loss rate) were known, and all BM97 had to do was to postulate the existence of a magnetic field in this star, which they computed to have an intensity $B_\star \sim 300$ G in order to confine the wind (for the simplified configuration of a dipole axis parallel to the rotation axis). This *predicted* magnetic field was subsequently detected by Donati et al. (2002), with an observed value $B_\star \sim 1$ kG, recently confirmed by Wade et al. (2006). In such a model, the reason for the X-ray rotational modulation is not the variation of the emission as the star rotates (since the magnetosphere is much larger than the star and much of its volume is optically thin to X-rays), but rather the extinction caused by the cooling equatorial disk. Fig. 3 is a sketch of the so-called "magnetically channeled wind shock" (MCWS) model as introduced by BM97. More elaborate numerical calculations (e.g., Townsend & Owocki 2005) have now refined this model, and recent high-resolution X-ray spectra of θ^1 Ori C have fully confirmed its validity (Schulz et al. 2003).

5. Magnetospheric accretion and star-disk interactions

There is widespread support, both observational and theoretical, for "magnetic accretion" in CTTS, i.e., infall of disk material onto the central star, channeled along (large-scale) magnetic field lines assumed to connect the stellar surface in the polar regions, and the inner disk in the vicinity of the corotation radius. As mentioned in Sect.1, the now classical theoretical picture is that of a dipolar magnetosphere, corotating with the star and with the same rotation axis ("parallel rotator", in pulsar parlance) (e.g., Shu et al. 1997).

However, a number of recent optical observations suggest the existence of a more structured magnetosphere, with discrete "accretion funnels" linking the disk to the star. This departure from cylindrical symmetry may have various natural causes. For instance, "oblique rotator" 3D MHD stationary models (Romanova et al. 2004) predict the existence of two main symmetrical accretion funnels and a distortion (warp) of the inner disk structure. The existence of an inner disk warp in AA Tau, which is seen nearly edge-on, was inferred from multicolor photometry by Bouvier et al. (1999, 2007a). These authors further suggested that the warp was caused by a star-disk oblique rotator interaction (see also Bouvier et al. 2007b). I would suggest another possible reason, in terms of local topological deformations of the magnetosphere caused by the underlying stellar activity-generated magnetic loops. But the interactions between the small-scale (activity) and the large-scale (dipolar) magnetic structures, obviously a very complex 3D MHD problem, has never been studied.

What about X-rays ? In the preceding sections, we have argued in favor of the widespread interpretation of X-rays from hundreds of young stars (Class I protostars, CTTS, WTTS) in terms of magnetic activity originating in a convective dynamo. However, in a so far handful of cases, the X-rays must be interpreted in terms of emission by shocks from magnetically channeled accretion –reminiscent, in a way, of the MCWS model proposed for some O stars, but with matter being channeled in the opposite direction.

The first case of "non-magnetic activity" X-ray emission from CTTS was reported by Kastner et al. (2002) for TW Hya. Thanks to its proximity ($d \simeq 60$ pc), TW Hya is one of the brightest CTTS, and high-resolution spectra could be obtained using the *Chandra* gratings. The analysis revealed several "anomalies": (i) an unusually high plasma density ($n_e \sim 10^{12}$cm^{-3}), i.e., an order of magnitude higher than the largest coronal densities; (ii) a very soft spectrum ($T_X = 2 \times 10^6$ K); (iii) a factor 2 higher Ne/O ratio compared to normal coronal abundances. Except for the Ne overabundance, Kastner et al. (2002), and subsequent studies (e.g., Robrade & Schmitt 2006), showed that, combined with the absence of time variability during the observations, the data could be interpreted in terms of an accretion shock near the stellar surface at the free-fall velocity of the gas ($v_{ff} \sim 200$ km s^{-1}). To date, two more CTTS (BP Tau and V4046 Sgr) have been found to show X-ray accretion spectral signatures of high plasma densities, determined independently of the temperature on the basis of the He-like NeIX and OVII triplet line ratios (Robrade & Schmitt 2006, Günther et al. 2006). An illustration of such a line spectrum in given on Fig. 4.

On the other hand, the presence of several accretion funnels connecting the disk to the star is now invoked to explain the factor $\sim 2-3$ deficiency in the X-ray emission of (accreting) CTTS and WTTS (Sect. 3), in terms of additional "self-shielding" provided by the discrete accretion flows (Preibisch et al. 2005).

As to the high Ne/O ratio in TW Hya, it remains unexplained. It is not observed in the other two known "accretion X-ray" CTTS. Drake et al. (2005), noted that a high Ne/O ratio meant a metal depletion in the accreting gas, that could be interpreted as a metal enrichment of dust grains upstream of the infalling material. They went as far as suggesting that this could be related to early planet formation in the disk, TW Hya being the most evolved among the "accretion X-ray" CTTS trio.

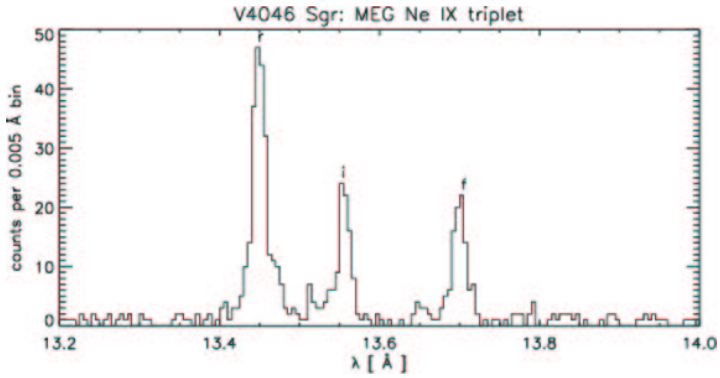

Fig. 4. The He-like Ne IX triplet in the X-ray spectrum of V4046 Sgr resolved by the *Chandra* medium-energy grating. The ratios between the lines (r= resonance, i = intercombination, f = fundamental) allow to compute directly the plasma density, and reveal the high densities ($n_e \sim 10^{12}$ cm^{-3}) typical of an accretion shock environment (Günther et al. 2006).

6. The mysterious Herbig stars

The so-called Herbig AeBe (HAeBe) stars are the young predecessors of intermediate-mass stars ($M_\star \sim 2-4\ M_\odot$), the future main-sequence A and B stars. They are entirely radiative and have relatively cool effective temperatures ($T_{eff} \sim 5,000-6,000$ K), and therefore are not expected to show any sign of magnetic activity, nor a significant wind. Yet, their detection rate in X-rays is quite high (∼ 76%, Stelzer et al. 2006). The X-ray luminosities, known for many years to reach levels in excess of the brightest TTS (e.g., Zinnecker & Preibisch 1994), as well as their soft spectra, preclude, contrary to the A stars (see above, Sect. 4), the presence of unresolved low-mass companions as the general explanation of their X-ray emission.

In the presumed absence of magnetic fields, some form of accretion shock can be invoked. However, because the stars are more massive than TTS, their free-fall velocities are larger ($v_{ff} \approx 500-600$ km s^{-1}), implying harder X-rays than observed. The high-resolution (*XMM* RGS) spectrum of AB Aur, the first among HAeBes, with its density-sensitive OVII triplet, does not show evidence for accretion-shock plasma densities (Telleschi et al. 2006), although a Ne excess is present in the low-resolution spectra of several HAeBe stars (Swartz et al. 2005).

UV observations by *FUSE* may hold the answer. In recent observations of HD 163296, Deleuil et al. (2005) found that the line profile of several strongly ionized heavy elements gave evidence for a weak wind ($\dot{M} \sim 7 \times 10^{-9}\ M_\odot$ yr^{-1}, $v_w \sim 300$ km s^{-1}), but with a much higher emissivity than a normal, freely expanding wind. These authors suggested that, instead of expanding freely, this wind is confined by a large-scale magnetosphere, with a predicted $B_\star \sim 700$ G, in a fashion very similar with the MCWS model of θ^1 Ori C. Independently, a Zeeman search for magnetic fields in three other HAeBe stars has resulted in one 5σ detection of the same order ($B_\star = 450 \pm 93$ G) (Hubrig et al. 2004; see also Hubrig et al. 2007).

Thus, the MCWS model appears promising also to explain the X-ray emission of some HAeBe stars, and implies the existence of magnetic fields in a significant fraction of them, which may be the predecessors to the Ap-Bp stars. In that sense, in X-rays HAeBe stars offer more similarities with OBA stars than with CTTS stars, despite the fact that, like CTTS, they are surrounded by circumstellar disks.

7. Complementary X-ray emitting environments

To complete the picture of X-ray emission associated with young stars, two other situations are possible.

• In the "accretion-ejection" paradigm, the corotation, due to magnetic locking, between the star and the inner disk, is assumed. If the central star is massive enough, and/or young enough, the timescale for corotation may be longer than the current age of the stars. CTTS are known to be slow rotators in general, suggesting the magnetic locking has indeed already taken place, while HAeBe stars tend to be fast rotators, opening up the possibility of incomplete magnetic locking, i.e., of a differential rotation between the star and the disk, and the possibility of "self-reconnection" of the star-disk magnetic configuration and resulting X-ray emission. It is in this context that Montmerle et al. (2000) explained the "triple flare" observed by *ASCA* in the Class I protostar YLW15. However, in spite of repeated observations of this star, and even during the two-week-long exposure of COUP, no other case of periodic X-ray flaring on young stars was found.

Star-disk interactions, without explicit evidence for periodic X-ray emission, have also been invoked to explain the emission of protostars in general (Preibisch 2004), and arguments in favor of large magnetic structures linking the star and the inner disk have been presented for some Orion TTS (Favata et al. 2005).

• In the context of shock X-ray emission, we have so far discussed accretion shocks. But shocks may also be produced by *ejection*, i.e., when jets, moving at velocities $v_{ej} \sim 200 - 400$ km s^{-1}, collide with the surrounding cold medium, for instance the dense envelope of protostars, or simply the ambient molecular cloud (in that case the higher-energy version of the usual shock interpretation of Herbig-Haro objects). For such shocks to be observable in X-rays, two conditions must be fulfilled: (i) sufficiently high shock velocities (in practice the high end of the observed jet velocities); (ii) sufficiently low extinction (which in general precludes observing shocks inside dense protostellar envelopes). These conditions are rather stringent, and may explain why so few cases have been observed. In the case of L1551, the X-ray emission was discovered with *XMM* (Favata et al. 2002), but it took the subarcsecond resolution of *Chandra* to assign the X-ray source to shocks inside the (binary) jet funnel within the envelope (Bally et al. 2003); a variety of shock configurations, using in particular the binary nature of the exciting source, have been proposed by these authors. The few other published cases correspond to bow shocks in the ISM, and can be explained in a straightforward way knowing the shock velocity (e.g., ρ Oph, Grosso et al. 2001; HH80/81, Pravdo et al. 2004; DG Tau A, Güdel et al. 2005).

8. Conclusions

What can X-rays tell us about accretion, mass loss, and magnetic fields in young stars ? To the title we have chosen for this review, we can now provide some answers.

• Magnetic activity-related X-ray emission, i.e., magnetic reconnection, is by far the most widespread mechanism in convective, low-mass young stars (Class I protostars, CTTS and WTTS alike). In a few cases there is indirect evidence for a star-disk reconnection in lieu of the common star-star reconnections (i.e., between magnetic loops on the star). In other words, as a rule X-rays can be safely taken a proxy for stellar magnetic fields, provided some signatures are checked: hard spectrum, flarelike light curve, coronal densities. Note that the large-scale ($R_c \approx 0.05$ AU) dipolar corotating magnetosphere (possibly oblique to the rotation axis) assumed to mediate accretion and ejection *cannot be detected in X-rays* if it is really in a steady state. If it is not and if reconnection occurs, then it is likely that the resulting X-ray emission will be qualitatively indistinguishable from the normal stellar activity. In other words, unfortunately X-rays *per se* cannot tell us anything about the magnetic "engine" that is supposed to make the accretion-ejection MHD mechanism work.

• However, there are a few exceptions (three to date) to the general magnetic activity picture. In these few cases, possibly because this solar-like activity is temporarily too low (magnetic cycles ?), X-rays come from accretion shocks. The signatures are clearly different from the preceding case: soft spectrum, absence of flares, densities much larger than coronal. High densities are best proven by He-like triplets, resolved by grating spectroscopy on *XMM* or on *Chandra*. Other forms of shocks can be produced by collisions between the jet and the surrounding medium (protostellar envelope, ambient ISM), in which case the emission is spatially distinct from the exciting star. Such cases are also physically interesting, but they are rare as well.

• Conversely, in the more massive stars, which have outer radiative layers, the dominant X-ray emission mechanism is shocks pervading their radiatively unstable winds. X-rays are then precious to probe the inner structure of the wind (density and temperature as a function of radius). However, a large fraction of the OB stars (up to $\sim$ 50% in the ONC, Stelzer et al. 2005) show various indications of magnetic fields when they are very young. If the magnetic fields are strong enough, then they can confine the wind inside a closed magnetosphere, and the resulting "magnetically channeled" flows from both hemispheres collide and emit shock X-rays, with an X-ray luminosity exceeding that of the standard wind instability mechanism. In that case, provided the viewing geometry is favorable, the X-ray rotational modulation directly reveals the existence of strong magnetic fields, as in the original case of θ^1 Ori C.

• The so-called "Herbig AeBe stars" are commonly referred to as T Tauri stars scaled up in mass, because of the presence of circumstellar disks and/or envelopes. However, from the point of view of X-ray emission, they seem to be more related to massive stars. In particular, at least in some cases of X-ray luminous HAeBe stars, the MCWS model may explain the X/UV emission. For less X-ray luminous HAeBe stars, the presence of a low-mass companion remains the most likely explanation for the X-ray emission, especially given that the X-ray emission of the (more evolved) A stars, when present, is fully consistent with the presence of such low-mass, TTS-like, unresolved companions. The Ap-Bp "magnetic" stars are thus likely the descendants of the strongly magnetized, X-ray luminous HAeBe stars. In analogy with the magnetized O stars, their magnetic fields are likely fossil, having somehow survived the formation stages.

All in all, we conclude that X-rays from young stars, which are thermal in the $\sim 0.1-10$ keV range covered by *Chandra* and *XMM*, always result from some combination of shocks and magnetic fields. On the one hand, magnetic activity dominates in the vast majority of low-mass stars, while on the other hand wind shocks dominate in a majority of high-mass stars. Although the number of "hybrid" cases (i.e., magnetic fields + shocks) is small, they give important insights into the physics of accretion (CTTS), and into the origin and early evolution of magnetic fields in massive stars (Ap-Bp stars).

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References

André, P., *et al.* 1988, ApJ, 335, 940
Babel, J., Montmerle, T. 1997a, A&A, 323, 121
Babel, J., & Montmerle, T. 1997b, ApJ, 485, L29
Bally, J., Feigelson, E.D., Reipurth, B. 2003, ApJ, 584, 843
Belloche, A., Hennebelle, P., André, P. 2006, A&A, 453, 145
Berghöfer, T.W., *et al.* 1997, A&A, 322, 167
Beuther, H., *et al.* 2007, in *Protostars and Planets V*, Eds. B. Reipurth, D. Jewitt, & K. Keil, (Tucson: University of Arizona Press), p. 165
Bonito, R., *et al.* 2007, A&A, 462, 645
Bouvier, J., *et al.* 1999, A&A, 349, 619
Bouvier, J., *et al.* 2007a, A&A, 463, 1017
Bouvier, J., *et al.* 2007b, in *Protostars and Planets V*, Eds. B. Reipurth, D. Jewitt, & K. Keil (Tucson: University of Arizona Press), p. 479
Brun, A. S., Zahn, J.-P. 2006, A&A, 457, 665

Deleuil, M., *et al.* 2005, A&A, 429, 247

Donati, J.-F., *et al.* 2002, MNRAS, 333, 55

Donati, J.-F., *et al.* 2007, in *14th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, Ed. G. van Belle, ASP Conf. Ser., in press (astro-ph/0702159)

Drake, J. J., Testa, P., Hartmann, L. 2005, ApJ, 627, L149

Favata, F., *et al.* 2002, A&A, 386, 204

Feigelson, E. D., & Montmerle, T. 1999, ARA&A, 37, 363

Feigelson, E. D., *et al.* 2005, ApJS, 160, 379

Gagné, M., et al. 1997, ApJ, 478, L87

Getman, K. V., et al. 2005, ApJS, 160, 319

Giardino, G., *et al.* 2007, A&A, 463, 275

Grosso, N., *et al.* 2001, A&A, 380, L1

Güdel, M. 2004, Astr.Ap.Rev., 12, 71

Güdel, M., *et al.* 2005, ApJ, 626, L53

Güdel, M., *et al.* 2006a, A&A, in press (astro-ph/0609160)

Güdel, M., *et al.* 2006b, A&A, in press (astro-ph/0609182)

Günther, H. M., *et al.* 2006, A&A, 459, L29

Hamaguchi, K., *et al.* 2006, in *The X-ray Universe 2005*, Ed. A. Wilson, ESA SP-604, p.33.

Hillenbrand, L. A. 2006, in *A Decade of Discovery: Planets Around Other Stars*, Ed. M. Livio, STScI Symposium Ser., 19, in press

Hubrig, S., Schöller, M., Yudin, R. V. 2004, A&A, 428, L1

Hubrig, S., *et al.* 2007, A&A, 463, 1039

Kastner, J. H., *et al.* 2002, ApJ, 567, 434

Kudritzki, R.-P., & Puls, J. 2000, ARA&A, 38, 613

Kurosawa, R., Harries, T. J., Symington, N. H. 2006, MNRAS, 370, 580

Lucy, L. B. 1982, ApJ, 255, 286

MacDonald, J., Mullan, D. J. 2004, MNRAS, 348, 702

Micela, G., Favata, F. 2005, Sp. Sci. Rev., 108, 577

Michaud, G. 2004, in *The A-Star Puzzle*, Eds. J. Zverko et al., IAUS 224 (Cambridge, UK: Cambridge University Press), p. 173

Montmerle, T. 2001, Science, 293, 2409

Montmerle, T., *et al.* 2000, ApJ, 532, 1097

Owocki, S.P., & Cohen, D.H. 1999, ApJ, 520, 833

Nugis, T., Lamers, H. J. G. L. M. 2000, A&A, 360, 227

Ozawa, H., Grosso, N., Montmerle, T. 2005, A&A, 438, 963

Peres, G., Orlando, S., Reale, F. 2004, ApJ, 612, 472

Pravdo, S., Tsuboi, Y., Maeda, Y. 2004, ApJ, 605, 259

Preibisch, T. 2004, A&A, 428, 569

Preibisch, T., *et al.* 2005, ApJS, 160, 401

Pudritz, R. E., *et al.* 2007, in *Protostars and Planets V*, Eds. B. Reipurth, D. Jewitt, & K. Keil (Tucson: University of Arizona Press), p.277.

Reale, F., *et al.* 2004, A&A, 416, 733

Robrade, J., Schmitt, J. H. M. M. 2006, A&A, 449, 737

Romanova, M. M., *et al.* 2004, ApJ, 610, 920

Schulz, N. S., *et al.* 2003, ApJ, 595, 365

Shu, F. H., *et al.* 1997, Science, 277, 1475

Stassun, K. G. 2001, in *From Darkness to Light*, Eds. T. Montmerle & P. André, ASP Conf. Ser., 243, p.599

Stelzer, B., Flaccomio, E., Montmerle, T., et al. 2005, ApJS, 160, 557

Stelzer, B., et al. 2006, A&A, 457, 223

Strassmeier, K. G., Rice, J. B. 2006, A&A, 460, 751

Swartz, D. A., *et al.* 2005, ApJ, 628, 811

Tanuma, S., Shibata, K. 2005, ApJ, 628, L77

Telleschi, A., *et al.* 2007, A&A in press (astro-ph/0610456)

Townsend, R. H. D., Owocki, S. P. 2005, MNRAS, 357, 251

Trigilio, C., *et al.* 2004, A&A, 418, 593

Vuong, M.H., *et al.* 2004, A&A, 408, 581

Wade, G.A. 2005, in *Element Statification in Stars*, Eds. G. Alecian, O. Richard, & S. Vauclair, EAS Publ. Series, 17, p.227

Wade, G. A., *et al.* 2006, A&A, 451, 195

Wolk, S. J.; *et al.* 2005, ApJ, 160, 423

Yang, Hao, Johns-Krull, C. M., Valenti, J. A. 2007, ApJ, 133, 73

Zinnecker, H., Preibisch, T. 1994, A&A, 292, 152