

X-ray emission from massive stars with magnetic fields *

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We investigate the connections between the magnetic fields and the X-ray emission from massive stars. Our study shows that the X-ray properties of known strongly magnetic stars are diverse: while some comply to the predictions of the magnetically confined wind model, others do not. We conclude that strong, hard, and variable X-ray emission may be a sufficient attribute of magnetic massive stars, but it is not a necessary one. We address the general properties of X-ray emission from “normal” massive stars, especially the long standing mystery about the correlations between the parameters of X-ray emission and fundamental stellar properties. The recent development in stellar structure modeling shows that small-scale surface magnetic fields may be common. We suggest a “hybrid” scenario which could explain the X-ray emission from massive stars by a combination of magnetic mechanisms on the surface and shocks in the stellar wind. The magnetic mechanisms and the wind shocks are triggered by convective motions in sub-photospheric layers. This scenario opens the door for a natural explanation of the well established correlation between bolometric and X-ray luminosities.

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1 Introduction

Massive stars ($M_{\text{initial}} \geq 10 M_{\odot}$) are among the key players in the cosmic evolution. Early UV observations revealed that their outer envelopes are outflowing in the form of powerful stellar winds (Morton 1967). The winds of OB-type and Wolf-Rayet (WR) type stars are driven by radiative pressure on metal lines (CAK, Castor et al. 1975; Gräfener & Hamann 2005). In general, the wind power depends on the evolutionary status of the star and is strongest for the evolved WR-type stars. There are numerous observational and theoretical evidences that magnetic fields play an important role in inner as well as in outer layers of massive stars. Magnetic fields in massive stars have the potential to strongly influence stellar formation and evolution (e.g. Ferrario et al. 2009) and affect stellar winds (e.g. Babel & Montmerle 1997).

While direct measurements of magnetic fields have so far been possible only for the closest and brightest stars, the indirect evidence for their presence is wide spread. The wide range of observational phenomena, such as wind-line periodic variability (e.g. Hamann et al. 2001) and excess emission in UV-wind lines centered about the rest wavelength, are commonly explained by the influence that magnetic fields exert on stellar winds (e.g. Schnerr et al. 2008). Chemical peculiarity, specific pulsation behavior, and non-

thermal radio emission may be manifestations of magnetic fields in massive stars as well as their X-ray emission.

In this paper we consider the X-ray emission from massive stars and its possible association with magnetic phenomena. In Sect. 1 we address the “normal” massive stars, and put forward a hybrid scenario for their X-ray emission; in Sect. 2 we consider stars where magnetic fields have been directly measured; in Sect. 3 the influence of the X-ray emission on stellar winds is briefly discussed. In Sect. 5 we finally consider the X-rays from O-stars on the zero-age main sequence and from WR-stars; concluding remarks are given in Sect. 6.

2 Magnetic fields can be important to understand the X-rays from “normal” massive stars

Stars across the HR diagram emit X-rays. Low- and solar-mass stars possess X-ray emitting coronae which are powered by an outer convection zone via magnetic fields. Stars of spectral types earlier than $\sim A7$ have no outer convection zone and normally no surface magnetic field. This textbook picture was challenged by works of MacGregor & Cassinelli (2003) and most recently by Cantiello & Braithwaite (2011). They found that magnetic fields of sufficient amplitude to affect the wind could emerge at the surface via magnetic buoyancy and suggested that this type of surface magnetism could be responsible for photometric variability

* Based on observations obtained with XMM-Newton and Chandra.

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and play a role in the generation of the X-ray emission and wind clumping.

These theoretical insights in stellar structure are in a good agreement with what is known about X-ray emission from massive stars. Already first X-ray observations of O-stars by the *Einstein* observatory revealed the emission from high ions like S XV and Si XIII in the O9.7 Ib star ζ Ori (Cassinelli & Swank 1983). Interestingly, Berghöfer & Schmitt (1996) reported an X-ray flare from ζ Ori. The analysis of the high-resolution spectrum of ζ Ori revealed that the hottest plasma is located close to the stellar core and that the wind is quite transparent for X-rays (Waldron & Cassinelli 2001). Soon after a surface magnetic field on ζ Ori was detected by Bouret et al. (2008). Larger samples of X-ray spectra from O-type stars were analyzed in Leutenegger et al. (2006), Oskinova et al. (2006), Waldron & Cassinelli (2007), and Raassen et al. (2008). All these works agree that the hottest X-ray emitting plasma can be found within $0.5 R_*$ from the stellar surface while the cooler X-ray emitting gas is spread out through the extended stellar wind.

Cassinelli & Swank (1983) suggested that two mechanisms of X-ray emission could operate in massive stars: very hot, probably magnetically confined loops near the base of the wind and fragmented shocks embedded in the wind. Since the X-ray variability was already known to be less than about 1%, Cassinelli & Swank (1983) suggested that there are thousands of shock fragments in the wind. This is recently confirmed by newer data of better quality (Nazé et al. 2011). Radiation hydrodynamic simulations of the nonlinear evolution of instabilities in stellar winds were performed by Owocki et al. (1988). They demonstrated that X-ray emission can originate from plasma heated by strong reverse shocks, which arise when a high-speed, rarefied flow impacts on slower material that has been compressed into dense shells. Feldmeier et al. (1997) showed that in order to match the observed X-ray flux, the wind shocks must be triggered by an instability seed perturbation at the base of the stellar wind.

We suggest that these seed perturbations at the base of the stellar wind could be associated with subsurface convective regions. The following phenomenological picture of X-ray emission from hot massive stars is emerging: the subsurface convective regions caused by an opacity peak associated with iron could host a dynamo, producing magnetic fields reaching the surface. The surface magnetic structures could play a pivotal role in generating the hottest plasma observed in X-ray spectra (an example of such mechanism is considered in Waldron & Cassinelli 2009). The turbulent motions in the convective zone also provide the seed perturbations required to trigger sufficiently strong shocks to match the observed X-ray fluxes. Furthermore, as hydrodynamic simulations show, these instabilities result in the structuring of the cool wind into fragmented dense shells (colloquially speaking “clumps”). Such porous wind struc-

ture makes the wind relatively transparent for X-rays (Feldmeier et al. 2003).

The correlation between stellar bolometric and X-ray luminosity, $L_X \approx 10^{-7} L_{\text{bol}}$ is well established (most recently, Gagné et al. 2011; Nazé et al. 2011a), but is not well understood. In our new scenario the X-ray emission is correlated with the stellar parameters in a natural way, via the dependence of the properties of the convective zone on fundamental stellar parameters L_{bol} and T_{eff} . Cantiello & Braithwaite (2011) predict that the surface magnetic field strength is increasing for hotter and more luminous stars. The wind momentum is also increasing with luminosity (Puls et al. 1996). Thus, the ratio of the wind kinetic energy to the magnetic energy could remain constant for stars of different luminosities.

The $L_X \approx 10^{-7} L_{\text{bol}}$ correlations breaks down for stars with $\log(L_{\text{bol}}/L_{\odot}) \lesssim 4.4$ (Sana et al. 2006). Such stars are located within the β Cep-type instability domain in the HR-diagram and have specific a pulsational behavior explained by the κ -mechanism (Dziembowski & Pamiatnykh 1993). The break down of the $L_X \propto L_{\text{bol}}$ correlation for β Cep type pulsators provides further clues on the connection between the X-ray emission and the stellar structure.

A correlation between the X-ray and the effective stellar temperatures was found by Walborn et al. (2009) from their studies of high-resolution X-ray spectra of a sample of massive stars. It is interesting to note that in the time-dependent hydrodynamic simulations by Feldmeier et al. (1997) the velocity jump U of the wind shocks depends on the ratio between the period of the perturbations at the wind base, T_c , and the flow time, $T_{\text{flow}} = R_*/v_{\infty}$. According to Cantiello & Braithwaite (2011), the convective turnover time (\sim hr) is larger for more massive stars. Since $v_{\infty} \propto \sqrt{M_* R_*^{-1}}$, the velocity jump, i.e. the temperatures of the gas heated in the shock could be higher for more massive stars with higher T_{eff} .

3 Magnetic fields on massive stars are not necessarily manifested via strong, hard and variable X-rays

From the small-scale magnetic fields which we considered in previous section, we now turn to the large-scale organized fields that may be fossil in origin. Babel & Montmerle (1997) studied the case of a star with a stellar wind and a dipole magnetic field. They predicted that a collision between the wind components from the two hemispheres in the closed magnetosphere leads to a strong shock and characteristic X-ray emission. Based on this magnetically confined wind shock model (MCWS), the presence of a magnetic field on the O-type star θ^1 Ori C had been postulated. Direct confirmation of the magnetic field in this star by Donati et al. (2006a) proved that X-rays have large diagnostic potential in selecting massive stars with surface magnetic fields.

Using the parameters of θ^1 Ori C, ud-Doula & Owocki (2002) and Gagné et al. (2005) performed MHD simulations in the framework of the MCWS model and made predictions that can be directly compared with observations: (i) the hottest plasma should be located at a few stellar radii from the stellar surface at the locus where the wind streams collide; (ii) the X-ray emission lines should be rather narrow, because the hot plasma is nearly stationary; (iii) magnetic stars should be more X-ray luminous than their non-magnetic counterparts of similar spectral type; (iv) the X-ray spectrum of magnetic stars should be harder than that of non-magnetic stars, with the bulk of the hot plasma at the hottest temperature; (v) the X-ray emission should be modulated periodically as a consequence of the occultation of the hot plasma by a cool torus of matter, or by the opaque stellar core. All these predictions are fulfilled for θ^1 Ori C. This modeling success established the MCWS model as a general scenario for the X-ray emission from magnetic early type stars.

Meanwhile, new observations of X-rays from magnetic O-type stars have been obtained. A strong magnetic field (~ 1 kG) is detected on HD 108 (O7I) (Martins et al. 2010). However, the emission measure (EM) of the softer spectral component, with a temperature of ≈ 2 MK, is more than one order of magnitude higher than the EM of the harder component $T_{\max} \approx 15$ MK, contrary to the expectation of the MCWS model (Nazé et al. 2004). HD 191612 also has a ~ 1 kG strong magnetic field (Donati et al. 2006a). Nazé et al. (2010) demonstrated that the large EM at ≈ 2 MK and the broad X-ray emission lines of this star do not compare well with the predictions of the MCWS model. Overall, considering the analysis of X-ray observations of magnetic O stars, it appears that only one star, θ^1 Ori C, displays properties that are fully compatible with the predictions of the MCWS model.

Cassinelli et al. (2002) and Brown et al. (2008) studied the case of fast rotating magnetic massive stars, specifically addressing the formation of disks in classical Be-type stars. They showed that magnetic torquing and channeling of wind flow from intermediate latitudes of the stellar surface can, for plausible field strengths, create a dense disk a few stellar radii in extent. Li et al. (2008) proposed a model, where the X-rays are produced by wind material that enters the shocks above and below the disk region. The model by Li et al. predicts a relation between the X-ray luminosity normalized to the stellar bolometric luminosity (L_X/L_{bol}) and the magnetic field strength in Be-type stars.

An interesting and well-studied example of a star with quite strong surface magnetic field is τ Sco. It displays several unusual features: (1) redshifted absorption in UV P Cyg lines to approximately $+250$ km s $^{-1}$ suggestive of infalling gas, (2) unusually hard X-ray emission requiring hot plasma at temperatures in excess of 10 MK (Mewe et al. 2003; Wojdowski & Schulz 2005), (3) a complex photospheric magnetic field with open and closed field lines (Donati et al. 2006b).

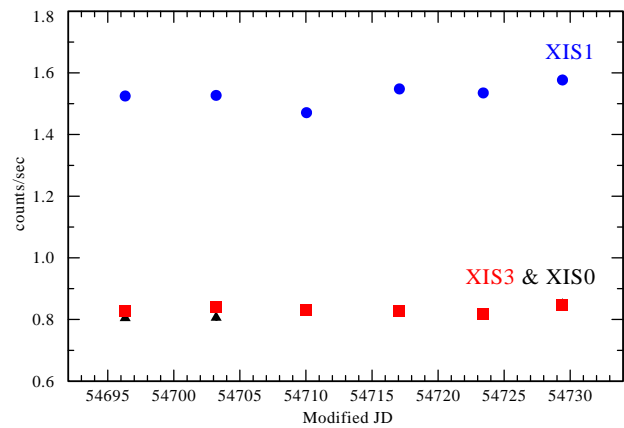


Fig. 1 (online colour at: www.an-journal.org) The Suzaku X-ray lightcurve of τ Sco. The upper curve is observations by the XIS1 detector in 0.2–12.0 keV band. The lower curves are observations with the XIS0 and XIS3 detectors (0.4–12 keV band). The error bars are smaller than the size of the symbols.

We obtained six observations of τ Sco with the Suzaku X-ray observatory to roughly sample its rotational period. The result of these observations were quite surprising (Ignace et al. 2010). No modulation of the X-ray emission on a level above 3% was detected (see Fig. 1), while the MCWS model predicts 40% (Donati et al. 2006b). It appears that the spatial distribution of the hot gas in τ Sco is different from the large-scale magnetic field distribution.

Donati et al. noted that the absence of the predicted high-amplitude X-ray modulation could be an indicator of smaller scale magnetic loops and confined hot gas across the stellar surface. Such loops would have evaded detection in their study. It is important to note that X-ray variability has not been detected from another magnetic B-star β Cep (Favata et al. 2009).

In Oskinova et al. (2011) we investigated the X-ray emission and wind properties of magnetic B-type stars. We studied all magnetic stars earlier than B2 with available X-ray data. Dedicated observations with XMM-Newton were performed for the three magnetic B-stars ξ^1 CMa, V2052 Oph, and ζ Cas (Oskinova et al. 2011). Two of them, V2052 Oph and ζ Cas, are detected in X-rays for the first time. We also searched the X-ray archives and collected the X-ray data for other magnetic early B-type stars.

One of the key findings of this study was that some magnetic early type stars have soft X-ray spectra. An interesting example is ζ Cas. This star is an oblique magnetic dipole with polar field strength ≈ 335 G (Neiner et al. 2003).

Our XMM-Newton observations of ζ Cas is the first to detect X-rays from this star. The EPIC spectra of ζ Cas and the best fit two-temperature model are shown in Fig. 2. The emission measure is dominated by plasma of 1 MK; a hotter, 4 MK component constitutes less than 20% of the total emission measure. There are no indications of a harder spectral component, making ζ Cas the softest X-ray source among all hot stars where magnetic field have been detected. The mean X-ray spectral temperature of ζ Cas is

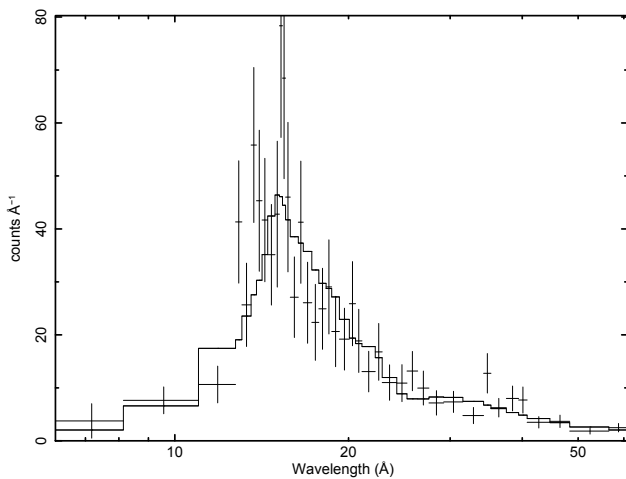


Fig. 2 XMM-Newton EPIC PN spectrum of ζ Cas and the best fit two-temperature model.

about 1 MK and its X-ray luminosity is $\approx 5 \times 10^{29}$ erg s $^{-1}$ (Oskinova et al. 2011).

Our study of magnetic early B-type stars revealed that the X-ray spectra and fluxes of early B-type stars with confirmed magnetic fields do not significantly differ from the X-ray spectra of stars where magnetic fields have not been found (e.g. Raassen et al. 2005). Similar conclusions were reached by Petit et al. (2011). It implies that either magnetic fields play only a minor role in the X-ray generation, or that magnetic fields are present (but remained yet undetected) in all early B-type stars emitting X-rays.

The X-ray emission from the peculiar magnetic Bp-type stars is diverse (Drake et al. 1994; Oskinova et al. 2011). While some stars display hard variable X-rays, others are rather soft sources. The X-ray luminosities differ among the otherwise similar stars in this group by more than two orders of magnitude.

We must conclude that the role of magnetism in the generation of X-ray emission in stellar winds, and consequently the physics of winds in magnetic stars, is not fully understood. New observational data and new MHD modeling of stellar winds shall bring future insights.

4 Magnetic fields and the X-ray emission strongly affect stellar winds

Information about stellar winds from B stars with magnetic fields was obtained by Oskinova et al. (2011) by modeling of the UV spectra. We found that the mass-loss rate in ζ Cas does not exceed $10^{-9.7} M_{\odot} \text{ yr}^{-1}$. This is ≈ 8 times smaller than the prediction of Babel (1996). Furthermore, we did not find any evidence for the predicted fast wind velocity of $v_{\infty} = 2100 \text{ km s}^{-1}$. Similarly, for all other stars in our sample, the mass-loss rates are an order of magnitude lower than predictions by Abbott (1982) based on the CAK theory.

We find that, although the X-rays strongly affect the ionization structure of the wind, this effect is not sufficient

in reducing the total radiative acceleration. When the X-rays are accounted for at the intensity and temperatures observed, there is still sufficient radiative acceleration to drive stronger mass-loss than we empirically infer from the UV spectral lines.

The emission measure of the hot X-ray emitting gas significantly (by 3–4 orders of magnitude) exceeds the emission measure of the cool wind, where the UV and optical spectra originate. This is an old standing problem, first pointed out by Cassinelli (1994) and Cohen et al. (1997). Our new analyses of better quality X-ray and optical and UV spectra further aggravate this problem.

5 Magnetic fields may be present on very young massive stars and on very old massive stars

X-ray observations of massive stars have the potential to probe magnetic fields at different evolutionary stages. The growing number of sensitive X-ray observations of young star-forming regions (SFRs) allowed the detection and study of recently formed massive stars. In presence of a strong surface magnetic field, a higher X-ray luminosity combined with a hard, sometimes non-thermal, spectrum, and X-ray variability may be expected. Chandra observations revealed that very young massive stars in the Galactic complex W3 are emitters of hard X-rays (~ 7 keV). Hofner et al. (2002) propose that magnetic reconnection events can be a mechanism responsible for this emission. However, they point out that the expected X-ray variability is detected only in one out of ten massive young stars. Magnetic fields have also been proposed to explain the hard X-ray spectrum ($kT_X \gtrsim 2$ keV) and synchrotron X-ray emission from the vicinity of the O star IRS 2, the primary source of ionization of the H II region RCW 38 (Wolk et al. 2002). The template magnetic massive star θ^1 Ori C is also located at the heart of a very young massive star cluster. Motivated by these observational findings, Schulz et al. (2003) proposed that the strength of stellar surface magnetic fields decline with stellar age.

To check whether the X-ray activity of massive stars is especially strong in youngest stars, we compiled in Table 1 a list of young ($\lesssim 2$ Myr) clusters observed by Chandra. We have inferred the X-ray luminosity of O stars in NGC 6618, NGC 6611, and the Hourglass and Rosette Nebulae using Chandra archival data. X-ray observations of O stars in the other clusters in Table 1 have been taken from the literature. Using the typical bolometric luminosity for each spectral type (Martins et al. 2005), we list in Table 1 the L_X/L_{bol} ratio for the earliest O star in each cluster. We also indicate whether the X-ray spectra are “hard”. In cases when analyses of the X-ray emission from the whole cluster population of O stars are available, the average ratio $\langle \log(L_X/L_{\text{bol}}) \rangle$ is given.

As Table 1 illustrates, the X-ray activity of massive stars differs significantly from cluster to cluster. Profoundly, in

Table 1 X-ray properties of O stars in some star clusters younger than 2 Myr.

Name	Age (Myr)	Sp. Type Earliest O-type Star	$\log(L_X/L_{\text{bol}})$ Earliest O-type Star	Presence of Hard Emission ($kT_X \gtrsim 2$ keV)	$\langle \log(L_X/L_{\text{bol}}) \rangle$ Ensemble of O Stars	Ref.
W3	0.2	O5–6 V	~ -6.7	yes		1
Trifid	0.3	O7.5 III	$\lesssim -7.2$	no	$\lesssim -7$	2
RCW 38	$\lesssim 1$	O5 V	-5.3	yes	-5.6	3
NGC 3603	1	O3–4 V	~ -6	yes	$-6 \dots -8$	4
NGC 6618	1	O4 V + O4 V	-6.7	yes		5
Trapezium	1	O6 V	-5.8	yes	-6.5	6
Hourglass	1	O7 V	-8	no		5
SMC N81	1	O6.5 V	-	-	$\lesssim -7$	
NGC 6611	1.3	O5 V	-6.8	no		5, 7
Rosette	1.9	O4 V	-7	no	~ -7	5

Notes: (1) Hofner et al. (2002); (2) Rho et al. (2004); (3) Wolk et al. (2006); (4) Moffat et al. (2002); (5) L_X is inferred using archival Chandra data; (6) Feigelson et al. (2002); (7) cluster parameters from Bonatto et al. (2006).

RCW 38 and the Orion Trapezium, the earliest O stars are more active than in others clusters of similar age. On the other hand, some stars are weak X-ray sources, e.g., Her 36 (O7V) in the Hourglass and HD 164492A (O7.5III) in the Trifid. Her 36 is of similar age and spectral type as θ^1 Ori C, yet the latter is significantly more X-ray luminous.

The hardness of the X-ray spectrum is not an unambiguous indication of the presence of a magnetic field. X-ray temperatures of several keV are expected and have been observed in binary systems. The probability that a massive star in a young cluster is a binary is high, therefore it is not surprising that many stars listed in Table 1 display the presence of $kT_X \gtrsim 2$ keV plasma in their spectra. This is likely the case of the Kleimann star, a massive O4+O4 binary ionizing the Omega Nebula cluster NGC 6618. While its spectrum is relatively hard, the broad-band X-ray luminosity is consistent with the canonical $L_X \approx 10^{-7} L_{\text{bol}}$ relation which holds also for binaries (Oskinova 2005).

The X-ray observations of the Trifid Nebula (Rho et al. 2004) allowed to resolve the central ionizing source into discrete components and revealed that an O7.5III star has a soft ($kT \approx 0.6$ keV) spectrum, while harder emission ($kT \approx 6$ keV) is associated with a B-type star which is blended with an unidentified source. Interestingly, X-ray flares were previously detected from B-type stars in two Orionis clusters: Trapezium and σ Ori (Sanz-Forcada et al. 2004; Stelzer et al. 2002).

Often, young SFRs where massive stars are just forming are located close to more evolved massive star clusters, suggesting a possible causal connection between massive star feedback and star formation. An example of such SFR is ON 2 located close to the massive star cluster Berkeley 87. Its X-ray properties were explored in Oskinova et al. (2010).

The most evolved star in Berkeley 87 is a rare WO-type star, WR 142. Stars of this spectral type are the ultimately latest evolutionary stage of a very massive stars (e.g. Sander et al. 2011). There are no direct measurements of magnetic fields on WR stars up to now (see Kholtygin et al., these proceed.). However, the X-ray properties of WR stars may

provide indirect evidence that magnetism plays a role also in the latest stages of stellar evolution.

Our XMM-Newton observation of the closest WO-type star WR 142 succeeded in detecting this object (Oskinova et al. 2009). It was also detected by the Chandra observatory (Sokal et al. 2010). Albeit the signal-to-noise of the observed spectrum was too poor for a detailed spectral analysis, from the hardness ratio Oskinova et al. (2009) concluded that the X-ray emission from this star is strongly absorbed in the wind, and is too hard to be explained by the wind-shock mechanism. We speculated that the hypothetical magnetic field can be responsible for this strong emission.

Our analysis of the optical spectrum of this star yielded the fundamental stellar parameters: $R_* = 0.5 R_\odot$, $T_{\text{eff}} = 160$ kK, $M_* = 5 M_\odot$. Remarkably, the optical emission line profiles in the spectrum of WR 142 have an unusual round shape. The formal rotational broadening models of these lines yield projected rotational velocity $v \sin i = 4000$ km s $^{-1}$. Thus, the star may be rotating at break-up velocity. These stellar parameters compare well with those expected for a SN or γ -ray burst progenitor (Paczynski 1998).

6 Concluding remarks

Surface magnetic fields on massive stars are both predicted theoretically and confirmed observationally. All massive stars emit X-ray radiation, but the connection between X-rays and magnetism in massive stars is not yet fully understood. The MCWS model can explain the strong, hard, variable X-ray emission from some magnetic dipoles. However there is no quantitative explanation for the soft and the constant X-ray emission that is observed in the majority of magnetic massive stars.

It was recently argued that *all* massive stars may have magnetic fields on their surface (Cantiello & Braithwaite 2011). In this paper we propose a new scenario of X-ray emission from a massive star, where the plasma on the surface is heated by magnetic mechanisms while the plasma

embedded in the stellar wind is heated by wind shocks. Both these mechanisms are triggered by sub-photospheric convective motions.

The advance of spectropolarimetric and X-ray observational techniques will undoubtedly lead to a new understanding of massive stars physics.

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