X-ray emission from magnetic massive stars

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Abstract

Magnetically confined winds of early-type stars are expected to be sources of bright and hard X-rays. In an attempt to clarify the systematics of the observed X-ray properties, we have analyzed a large series of Chandra and XMM observations, corresponding to over 100 exposures of 60% of the known magnetic massive stars listed recently by Petit et al. (2013, MNRAS, 429, 398). We notably show that the X-ray luminosity is strongly correlated with mass-loss rate, in agreement with predictions of magnetically confined wind models. We also investigated the behaviour of other X-ray properties (plasma temperature, absorption, variability), yielding additional constraints on models. This work not only advances our knowledge of the X-ray emission of massive stars, but also suggests new observational and theoretical avenues to further explore magnetically confined winds.

Reference : Nazé et al., submitted

Context

In the last decade, tens of massive stars were found to be strongly magnetic. Such magnetic fields are able to channel the stellar winds of these stars towards the magnetic equator, giving rise to **magnetically confined winds** (MCWs) which should emit X-rays. While the two prototypes (σ Ori E and θ Ori C) display high-energy emission in line with expectations, the situation appears more confused for other objects. We have therefore undertaken a systematic study of the full sample of magnetic massive stars.

X-ray luminosity

Observational results

If MCWs are responsible for producing X-rays, then some correlations between X-ray observables and stellar/wind/magnetic properties are expected. We first investigated the link between the X-ray emission levels and the mass-loss rates since shocks extract some of the wind kinetic energy to produce X-rays. Two groups of sources are found :

•**one group displays log(Lx/Lbol)=-6.23±0.07**, which is equivalent to Lx ∝ $\mathrm{Mdot}^{0.6}$ typical of radiative winds but with higher Lx/Lbol than for “normal” O-stars ; this group comprises all O-stars and six B-stars. Note that there are 2 cases of non-magnetic origin for X-rays (the fainter emission of ζ Ori, which has a very weak field + the bright emission of Plaskett’s star, probably linked to binary interactions)

•**the other group displays Lx ∝ $\mathrm{Mdot}^{1.4}$**

Note that faint/non-detections agree well with these relations.

We examined alternative relations (with Lbol, wind density, Hα emission strength) as well as more complicated relations (e.g. considering dependences on Mdot and magnetic field strength): none was found significantly better.

Comparison with theoretical predictions

Babel & Montmerle (1997, A&A, 323, 121) proposed Lx ∝ Mdot x $B^{0.4}$ but this scaling seems to be inadequate for the lowest and highest mass-loss rates, and the predicted emission level is too high by 1.8 dex.

New MHD simulations by ud-Doula et al. (2014 , in press, arxiv:1404.5336) re-investigated the X-ray emission of MCWs, showing the impact of shock retreat effects. Their predictions appear much better **in line with the observational results**, both for observed trends and emission levels. **A few discrepancies** remain, though, and could not be explained – e.g. a few B-stars with bright Lx but low Mdot: some of them are fast rotators but not all.

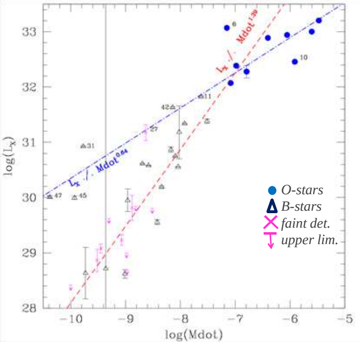
X-ray absorption

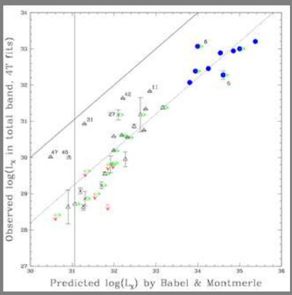
Spectral fits allowed for the possibility of absorption in addition to the interstellar one. In general, it is not needed for B-stars, while O-stars require an amount comparable to what is needed for “normal” O-stars. No correlation with stellar/wind/magnetic parameters is found. The only special case is NGC1624-2, the most magnetic O-star, whose dense magnetosphere leads to the presence of high absorption.

Data

To ensure a high homogeneity and to maximize the number of detections, we focused on **CCD spectra in the 0.5-10. keV range**, i.e. XMM-EPIC and Chandra-ACIS (Swift, Suzaku, ASCA did not yield additional detections). Over 100 exposures are available for 39 targets (out of the 64 of the Petit et al. catalog). In the magnetic confinement-rotation diagram, these targets are well distributed, so we are not sampling a particular subpopulation.

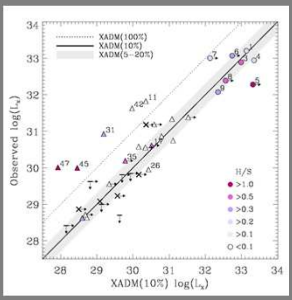
Amongst them, there are 6 non-detections, 5 faint detections, and 28 detections bright enough for spectra to be extracted. These spectra were fitted by absorbed optically-thin plasma (with free temperatures or a set of fixed temperatures, both methods yielding similar results).

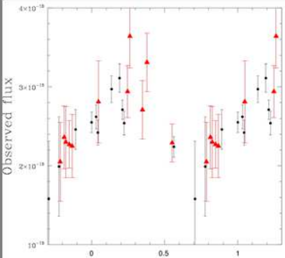


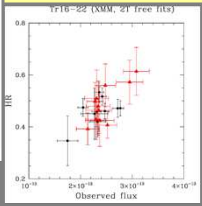


Top left: X-ray luminosity as a function of mass-loss rates, with the detected trends superimposed. Plaskett’s star is #6, ζ Ori #10.

Right: Comparison of observed and predicted luminosities for the Babel & Montmerle formula (top, with the dashed line 1.8 dex below perfect agreement) and the ud-Doula et al. MHD simulations (bottom, for several efficiencies). The agreement is better with the latter.







Discovery of the variations of Tr16-22 thanks to XMM *Left:* X-ray emission phased with the 54d period (2003 data in red); *Bottom:* changes in luminosity and hardness are correlated.

X-ray spectral shape

Hardness ratios and average temperatures were also derived from the fits. Magnetic O-stars clearly are harder/hotter than their non-magnetic siblings, but most of the B-stars show low hardness ratios. **No correlation was found with stellar/wind/magnetic parameters; theoretical expectation of hotter plasma for higher confinement or mass-loss rates is not verified.** Also, the overluminous (compared to predictions) B-stars do not necessarily show peculiar temperatures.

Variation of the X-ray emission

When several exposures are available, we have examined the X-ray variability. Three behaviours are detected :

- **constant emission**, as expected from the properties of the target (pole-on geometry for HD 148937, large magnetosphere for σ Ori E, non-magnetic origin of the X-rays for ζ Ori).
- **flux changes without spectral changes** (HD47777 and β Cep) but they cannot be linked to MCWs with current data.
- **flux and spectral changes** (Tr16-22, HD191612, NU Ori, θ Ori C), in harmony with the stellar rotation : they are due to occultation effects in stratified MCWs. Note however that two trends are seen : either harder or softer when brighter. Detailed models are now needed to explain this behaviour.