Early Magnetic B-Type Stars: X-ray Emission and Wind Properties

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Early magnetic B-type stars

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Massive Stars and Stellar Winds

Initial mass $M_* > 8M_\odot$

Main Sequence: OB-type

Fast evolution ($\sim$Myr) $\rightarrow$ trace star formation

**Hot.** $T_{\text{eff}} > 10,000$ K $\rightarrow$ high surface brightness

Photon momentum $\rightarrow$ acceleration of matter

Radiative acceleration larger than gravitation $\rightarrow$ supersonic **STELLAR WIND**
The evolution of massive stars

Evolution $\leftarrow$ stellar wind, rot, B (?)

Stellar structure: no outer convective zone (no dynamo)
Chemically Peculiar (classical) magnetic ApBp stars

Wide range of spectral types. Dipole kG-strong magnetic fields

σ Ori E - cartoon from D. Groote homepage

Winds $\rightarrow$ Low Plasma- $\beta$ $\rightarrow$

Stellar wind dynamics is dominated by B
Magnetically Confined Wind Shock (MCWS) model (Babel & Montmerle 1997ab)

- $\theta^1$ Ori C: a story of success
  - Babel & Montmerle 97; Stahl et al. 96, 08; Weigelt et al. 99; Donati & Wade 99; Schulz et al. 00, 02; Donati et al. 02; Ud-Doula et al. 02, 06, 08, 09; Naze et al. 10.

- Dipole kG magnetic field - oblique magnetic rotator

- Multiwavelength properties are well explained and confirmed by MHD simulations

- An accepted template of a magnetic OB star

adopted from Gagné et al. 05
MCWS model predictions

MCWS: well defined model predictions:

- $L_X/L_{bol} \gg 10^{-7}$
- DEM peaking at 20 MK
- Narrow X-ray line profiles
- X-ray periodic variability
- X-ray formation at few $R_*$

Can X-rays be used as a diagnostic tool to reveal magnetic massive stars?

adopted from Gagné et al. 05
X-ray emission and stellar winds

Last decade: **boom** in the detections of magnetic fields on massive stars (Donati & Landstreet 2009)

- Collect all existing X-ray data on early type (earlier than B2) B-stars. Dedicated XMM-Newton observations for three stars, $\xi$1 CMa, $\zeta$ Cas, V2052 Oph: two are detected for the first time
- **The complete sample of early B-type stars with detected magnetic fields and existing X-ray observations to date.** (Oskinova et al. 2011)
- To obtain quantitative information on stellar winds: model UV lines using state-of-the-art stellar atmosphere code PoWR.
X-ray spectra of magnetic B-stars

Example: XMM-Newton observations of $\xi^1\text{CMa}$: $B_{\text{pol}} = 5.3$ kG

- The bulk of hot gas $T_X = 1$ MK (except $\tau\text{ Sco, } \sigma\text{ Ori E}$)
- The $\log(L_X/L_{\text{bol}})$ ratio in the range $-5.6 \ldots -8.5$
X-ray variability

- Magnetic configuration of $\tau$ Sco
- Strongly assymetric, not dipole
- Correlation of X-ray flux with $B$:
  - Wind confined models
  - coronal loop models
- **Observe at different rotational phases**

Donati et al. 2003
X-ray variability

- Magnetic configuration of $\tau$ Sco
- Strongly asymmetric, not dipole
- Correlation of X-ray flux with B:
  * Wind confined models
  * coronal loop models
- No X-ray variability

Ignace et al. 2010

Donati et al. 2003
**X-ray variability**

- Magnetic configuration of \( \tau \) Sco
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\[ \text{counts/sec} \]

- \( \beta \) Cep  soft spectrum, no variability, narrow lines (Favata etal 09)
- \( \sigma \) Ori E hard spectrum, flare (?) (Groote etal 04, Sanz-Forcada etal 2004)
- \( \theta^1 \) Ori C hard spectrum, periodic X-ray variability (Gagne 1998, +)
Correlation with stellar parameters

$L_X$ of $\beta$ Cep-type stars vs. magnitude of pulsation (upper panel) and pulsational period (lower panel)

Our sample is small (11)

- No correlation with $P_{rot}$
- No correlation with $B$
- No correlation with $P_{puls}$
- No tight correlation with $L_{bol}$
Correlation with stellar parameters

$L_X$ of β Cep-type stars vs. magnitude of pulsation (upper panel) and pulsational period (lower panel)

Our sample is small (11)
- No correlation with $P_{\text{rot}}$
- No correlation with $B$
- No correlation with $P_{\text{puls}}$
- No tight correlation with $L_{\text{bol}}$

What about stellar winds?
Stellar Wind Analysis

- PoWR NLTE stellar atmospheres
- Iron Line blanketing
- Co-moving frame RT
- Complex atomic data
- Expanding atmospheres
- Photosphere + wind
- X-Rays

Optical spectrum of $\xi$ CMa (blue) vs. PoWR model (red)
X-rays are important for correct mass-loss rate diagnostics

The effect of ionization by X-rays on CIV line

The IUE spectrum of τ Sco (detail)

Blue observations

Model without X-rays; with X-rays; $\log(\dot{M}) = 10^{-9.3} \ M_\odot/\text{yr}$
X-rays are important for correct mass-loss rate diagnostics

The effect of ionization by X-rays on SiIV line

The IUE spectrum of β Cep (detail)

Blue observations

Model with X-rays; $\log(\dot{M}) = 10^{-9.1} M_\odot/yr$
The results of the wind analysis diagnostics

- The wind velocities are low (approx. 700 km/s)

- The mass-loss rates are low \( \log(\dot{M}) \sim -10 \)

- The radiative pressure is capable of driving the winds a factor of few stronger: "Weak Winds"

- The emission measure of hot X-ray emitting gas is much higher than the emission measure of cool gas we see in the UV: the hot plasma is very dense or has large volume

- Low-\( \beta \) plasma: the wind motion is dominated by \( B \)
Comparing with the observations diagnostics

- We know $B$ strength and configuration from other groups.
- We know X-rays emission ($L_{X&M}, kT_X$) from observations.
- Plug it in the PoWR model, compute UV spectra, obtain stellar wind parameters.
- Use $B$, $\dot{M}$, $v_{\text{wind}}$ as parameters for MCWS model.
- Compare predicted $L_X$, $kT_X$, DEM with the observed.
- How well does MCWS model works? Check alternative models.
Conclusions (followed up by open questions)

Based on our comprehensive study of the complete (present) sample of massive B-stars with B

- MCWS model can explain observed ”normal” $L_X$: the stellar winds are weaker than theoretically predicted by the stellar wind theory.
- MCWS doesn’t seem be able to explain the DEM as obtained from the observations (too low temperatures)
- X-ray properties of magnetic B-stars are diverse: no tight $L_X$-$L_{bol}$ correlation: some sources are hard some sources are soft.
- Soft and intrinsically faint X-ray stars can be magnetic.
- X-rays must be incorporated in stellar spectral analysis to obtain the correct ionization structure and mass-loss rate.
Open Questions

- Why B-stars have weak winds?
- Origin, incidence, and structure of B?
- How X-rays are generated: MCWS model is not be a unique possibility?
- Many further questions....
Thank you!