Probing the stellar wind environment of Vela X-1

With MAXI:

hints for a multi-tasking accretion wake

Christian Malacaria (IAAT + RIKEN)
Mihara T., Makishima K., Matsuoka M., Morii M., Sugizaki M. (RIKEN), Santangelo A. (IAAT)
Vela X-1: Wind-fed eclipsing HMXB

$D \sim 2 \text{ kpc}$

$M_{\text{NS}} \sim 1.8 \ M_{\odot}$

$P_{\text{orb}} \sim 8.9 \ \text{d}$

$M_{\text{opt}} \sim 24 \ M_{\odot}$

$R_{\text{opt}} \sim 31 \ R_{\odot}$

$P_{\text{spin}} \sim 283 \ \text{sec}$

$\dot{M} \sim 2 \times 10^{-6} \ M_{\odot} / \text{yr}$

Separation $\sim 0.6 \ R_{\text{opt}}$

$e \sim 0.089$
Photoionization wake + accretion wake + tidal stream
(see Kaper et al. 1994 and references therein)

\[ \phi = 0.25 \]

\[ \phi = 0.75 \]

\[ \phi = 0.5 \]
(Inferior Conjunction)

\[ N_H \] increases at later phases (this is well known in literature)

Fig. From Malacaria et al., submitted to A&A
MAXI/GSC Vela X-1 orbital light curve examples

4 – 10 keV

10 - 20 keV
MAXI/GSC Vela X-1 orbital light curve examples
MAXI/GSC Vela X-1 orbital light curve: 4 years folded data
We perform analysis separately for **DOUBLE-PEAKED** and **STANDARD** samples.
ISGRI (20 – 60 keV) dip

Fig. from Fuerst et al. 2010: 8 orbital lightcurves

Orbital phase-resolved histograms of the ISGRI 20-60 keV data
Accretion wake properties

Fig. from Mauche et al., 2008

FIGURE 2. Color-coded maps of (a) $\log T (K) = [4.4,8.3]$, (b) $\log n (cm^{-3}) = [7.4,10.8]$, (c) $\log v (km \, s^{-1}) = [1.3,3.5]$, and (d) $\log \xi (erg \, cm \, s^{-1}) = [1.1,7.7]$ in the orbital plane of Vela X-1. The positions of the B star and neutron star are shown by the circle and the “×,” respectively. The horizontal axis $x = [-5,7] \times 10^{12} \, cm$ and the vertical axis $y = [-4,8] \times 10^{12} \, cm$.

$T \sim 10^8 \, K$ \hspace{1cm} $n \sim 10^8 - 10^{12} \, cm^{-3}$ \hspace{1cm} $\xi \sim 10^4 \, erg \, cm \, s^{-1}$ \hspace{1cm} $L \sim R_B \sim 10^{12} \, cm$
Thomson scattering contribution

X-ray absorption accounts for $N_H \sim 3 \times 10^{23} \text{ cm}^{-2}$:

$$w_{abs} = F(E) = \exp[N_H \sigma(E)]$$

To this, we need to take into consideration Thomson scattering contribution:

$$M(E) = \exp[N_H \sigma_T]$$

An hot (ionized) and dense enough accretion wake can produce enough scattering to show a double-peaked sample.
Orbital Phase-resolved spectroscopy: Cutoff Power-law

\[ F(E) = K E^{-\Gamma} \exp\left[ E / E_{fold} \right] + \text{BlackBody} \]
Cutoff Power-Law contour plots

$\chi^2$ contour plots for two parameters, $N_H$ and $\Gamma$, for the two analyzed samples.

Largest contours correspond to $\chi^2_{\text{min}} + 4.61$ (90% for 2 parameters of interest)

No physical mechanism found!
Orbital Phase-resolved spectroscopy: Partial Covering

Successfully used by Fuerst et al. 2010 for Vela X-1

\[ F(E) = f \exp[-N_H \sigma(E)] + (1 - f) \]

We need a partial covering component only for the central phase bin(s) of both the samples.
Orbital Phase-resolved spectroscopy: Partial Covering

Successfully used by Fuerst et al. 2010 for Vela X-1

\[ F(E) = f \exp\left[-N_H \sigma(E)\right] + (1-f) \]

We need a partial covering component only for the central phase bin(s) of both the samples

Wobbling accretion wake (oscillations averaged over many orbits)
Orbital Phase-resolved spectroscopy: Partial Covering

SUCCESSFULLY USED BY FÜREST ET AL. 2010 FOR VELA X-1

\[ F(E) = f \exp[-N_H \sigma(E)] + (1-f) \]

We need a partial covering component only for the central phase bin(s) of both the samples

Wobbling accretion wake (oscillations averaged over many orbits)

Intrinsically inhomogeneous accretion wake
An intrinsically inhomogeneous accretion wake

Figure from Blondin et al., 1991

Clumps expected (Runacres & Owocki 2005) and observed (Goldstein et al. 2004) and also indicated as responsible for the X-ray variability (Kreykenbohm et al. 2008, Martinez-Nunez et al. 2014)
Rising of the Clumps

Sundqvist & Owocki, 2013

If the high X-ray variability comes from a clumpy environment, but the clumps form only after than $1.1 \ R_B$, where do the inhomogeneities come from?
A necessary Neutron Star

The Neutron Star itself may form clumps at its passage, which are then accreted feeding the X-ray variability

Credit: ESA/ AOES Medialab
Summary 1st part

- We extracted a double-peaked sample (~15% of the total) in both 4-10 and 10-20 keV

- Explaining the dip by solely absorption would require $N_H \sim 10^{24}$ cm$^{-2}$, which is not observed in our analysis

- A possible contribution to the dip may come from Thomson scattering by an hot ionized accretion wake
Summary 2\textsuperscript{nd} part

- A cutoff power-law model shows photon index modulation with the orbital phase, which likely hints to inadequacy of this model.

- Photon index modulation is avoided if a partial covering component is included around the inferior conjunction.

- Partial covering may come from either a wobbling or an intrinsically inhomogeneous accretion wake.

- An inhomogeneous accretion wake has interesting consequences about Vela X-1 X-ray variability and feedback.
Thank you!

Malacaria Christian
Institute for Astronomy and Astrophysics of Tuebingen
(stay tuned on A&A)

Email me:
malacaria@astro.uni-tuebingen.de
Backslides
(Personal opinions) On the accretion wake changes

• Variation of stellar wind velocity

• Variation of stellar wind $M\dot{}$

• Feedback coupling with the Stromgren sphere
Perturbation timescale

\[ \tau_{\text{pert}} = \frac{R_{\text{ion}}}{V_{\text{orbit}}} \quad 5.5 \text{ hours} \]

Maximum time observed for flares in Vela X-1
(Ducci et al. 2009, Martinez-Nunez et al. 2014)

Bremsstrahlung cooling time:

\[ 10^{11} \sqrt{T/n} \sim 10^5 \text{ s} \sim 1 \text{ day} \]
3D accretion wake

Figure from Mauche et al. 2008