Highly structured Wind in Vela X-1: Giant Flares and Offstates

Ingo Kreykenbohm
(Dr. Karl-Remeis-Sternwarte, Bamberg)

J. Wilms, P. Kretschmar, J. Torrejon, K. Pottschmidt, M. Hanke,
A. Santangelo, C. Ferrigno, R. Staubert

ESAC Science Seminar, November 20, 2008
X-ray Binaries

- accretion most efficient energy source!
- 1 accreted electron: 100keV
- accretion rate: $10^{17}$ g/sec
X-ray Binaries

- accretion most efficient energy source!
- 1 accreted electron: 100keV
- accretion rate: $10^{17}$ g/sec
- compact object + optical star
X-ray Binaries

- accretion most efficient energy source!
- 1 accreted electron: 100keV
- accretion rate: $10^{17}$ g/sec

- compact object + optical star
- classification
  - LMXBs
X-ray Binaries

- accretion most efficient energy source!
- 1 accreted electron: 100keV
- accretion rate: $10^{17}$ g/sec

- compact object + optical star
- classification
  - LMXBs
    - Roche Lobe Overflow
    - accretion disk
    - old system
    - weak magnetic field
    - no pulsations
X-ray Binaries
X-ray Binaries

- compact object + optical star
X-ray Binaries

- compact object + optical star
- classification
  - HMXB
X-ray Binaries

- compact object + optical star
- classification
  - HMXB

Wind accretion
Be mechanism
X-ray Binaries

• compact object + optical star
• classification
  ▶ HMXB

- Wind accretion
- Be mechanism
- young systems
- strong magnetic field
- pulsations
X-ray Pulsars
X-ray Pulsars

- Neutron stars have strong magnetic field: $B \sim 10^{12}$ G
  (flux conservation in SN collaps)
X-ray Pulsars

- Neutron stars have strong magnetic field: $B \sim 10^{12} \text{ G}$ (flux conservation in SN collaps)
- Material couples to magnetic field lines
- Material is channeled onto the magnetic poles
  $\Rightarrow$ hotspots emerge
X-ray Pulsars

- Neutron stars have strong magnetic field: \( B \approx 10^{12} \) G (flux conservation in SN collaps)
- Material couples to magnetic field lines
- Material is channeled onto the magnetic poles ⇒ hotspots emerge
- Offset of magnetic and rotational axis ⇒ pulsations
strong magnetic field: electron energies are quantized in Landau levels:
Cyclotron Lines

**strong** magnetic field: electron energies are quantized in **Landau levels**:

\[
E_{\text{cyc}} = \frac{\hbar e}{m_e c^2} = 11.6 \text{ keV} \left( \frac{B}{10^{12} \text{G}} \right)
\]

**12-B-12**
Cyclotron Lines

**strong** magnetic field: electron energies are **quantized** in **Landau levels**:

\[
E_{\text{cyc}} = \frac{\hbar e}{m_e c^2} = 11.6 \text{ keV} \left( \frac{B}{10^{12} \text{G}} \right)
\]

Cyclotron resonance scattering features (**CRSFs**)
strong magnetic field: electron energies are quantized in Landau levels:

\[ E_{\text{cyc}} = \frac{\hbar e}{m_e c^2} = 11.6 \text{ keV} \left( \frac{B}{10^{12} \text{G}} \right) \]

Cyclotron resonance scattering features (CRSFs)

\[ E_n = n E_{\text{cyc}} = (1 + z) E_{n,\text{obs}} \]
strong magnetic field: electron energies are quantized in Landau levels:

\[ E_{\text{cyc}} = \frac{\hbar e}{m_e c^2} = 11.6 \text{ keV} \left( \frac{B}{10^{12} \text{G}} \right) \]

Cyclotron resonance scattering features (CRSFs)

\[ E_n = n E_{\text{cyc}} = (1 + z) E_{n,\text{obs}} \]

First observation by Truemper et al. in 1977 in Hercules X-1:
strong magnetic field: electron energies are quantized in Landau levels:

\[ E_{\text{cyc}} = \frac{\hbar e}{m_e c^2} = 11.6 \text{ keV} \left( \frac{B}{10^{12} \text{G}} \right) \]

Cyclotron resonance scattering features (CRSFs)

\[ E_n = n E_{\text{cyc}} = (1 + z) E_{n,\text{obs}} \]

First observation by Truemper et al. in 1977 in Hercules X-1:
Cyclotron Lines

**strong** magnetic field: electron energies are **quantized** in **Landau levels**:

\[ E_{\text{cyc}} = \frac{\hbar e}{m_e c^2} = 11.6 \text{ keV} \left( \frac{B}{10^{12} \text{G}} \right) \]

**Cyclotron resonance scattering features (CRSFs)**

\[ E_n = n E_{\text{cyc}} = (1 + z) E_{n,\text{obs}} \]

First observation by Truemper et al. in 1977 in Hercules X-1:

\[ E_{\text{cyc}} = 40 \text{ keV} \]
Vela X-1

- NS + B0.5Ib GP Vel
  super giant companion
- dense Wind:
  $\dot{M} = 4 \times 10^{-6} \, M_\odot$
- orbital Period 8.96 d
- heaviest known neutron star: $1.8 \, M_\odot$
Vela X-1

- NS + B0.5Ib GP Vel super giant companion
- dense Wind: \( \dot{M} = 4 \times 10^{-6} \, M_\odot \)
- orbital Period 8.96 d
- heaviest known neutron star: 1.8 \( M_\odot \)
- typical XRB spectrum CRSFs at 25 and 50keV
History

- Vela X-1 known to be variable:
  - Flares: ROSAT, Granat, EXOSAT, RXTE

Haberl (1994)
History

- **Vela X-1** known to be variable:
  - **Flares**: ROSAT, Granat, EXOSAT, RXTE

Haberl & White (1990)
History

- Vela X-1 known to be variable:
  - Flares: ROSAT, Granat, EXOSAT, RXTE
History

- Vela X-1 known to be variable:
  - Flares: ROSAT, Granat, EXOSAT, RXTE
  - “Dips”: Tenma, Granat, RXTE
- various ideas, cause unknown
• Vela X-1 known to be variable:
  • Flares: ROSAT, Granat, EXOSAT, RXTE
  • “Dips”: Tenma, Granat, RXTE
• various ideas, cause unknown
2.3 Crab
Fluence: $1.2 \times 10^{41}$
INTEGRAL

**Diagram Description:**

- **Countrate (counts/s):** The graph shows the countrate for different flares over time.
- **Hardness Ratio:** A second axis (b) indicates the hardness ratio, with values ranging from -0.85 to about -0.70.
- **Flares:** Flares 1 through 5 are labeled, with Flare 1 being the most prominent.
- **Timeline:** The timeline spans from November 2003 to December 2003, with specific event markers such as Rev 137 to Rev 141.

**Notes:**

- A short flare is indicated on the graph.

**Legend:**

- Red line represents countrate.
- Blue line represents hardness ratio.

**Graph Details:**

- The graph is divided into two axes: one for countrate and one for hardness ratio.
- The x-axis represents time from November 27, 2003, to December 12, 2003.
- The y-axis for countrate ranges from 0 to 400 counts/s.
- The y-axis for hardness ratio ranges from -0.85 to approximately -0.70.
INTEGRAL

Flare 1
Flare 2
Flare 3
Flare 4
Flare 5

Rev 137
Rev 138
Rev 139
Rev 140
Rev 141

Count rate (counts/s)

Hardness Ratio

Flare 3
Flare 4
Flare 5

November 2003
December 2003

Flare

Fluence: $1.2 \times 10^{41}$

long flare
Flare 1:
- Peak: 5.2 Crab
- Duration: 11200 sec
- Spectrum “softer”
- Fast rise: $\tau = 0.15$

$$\tau = \frac{T_{\text{rise}}}{T_{\text{total}}}$$
Flares

Flare 1:
- Peak: 5.2 Crab
- Duration: 11200 sec
- Spectrum “softer”
- Fast rise: $\tau = 0.15$

Flare 3:
- Peak: 5.3 Crab
- Duration: 1800 sec
- Fast rise: $\tau = 0.28$

\[ \tau = \frac{T_{\text{rise}}}{T_{\text{total}}} \]
signifiant spectral change
Hardness

significant spectral change
Hardness

Significant spectral change

No change
HID

Flare 1  Flare 2  Flare 3  Flare 4  Flare 5

\( \tau = 0.15 \quad \tau = 0.83 \quad \tau = 0.28 \quad \tau = 0.13 \quad \tau = 0.63 \)
- hardness mostly constant (no evolution w/ phase)
• hardness mostly constant (no evolution w/ phase)
• significant change during Flares 1 and 4
• NO change during Flares 2 and 5
• hardness mostly constant (no evolution w/ phase)
• significant change during Flares 1 and 4
• NO change during Flares 2 and 5

➡ two types of flares:
  ➤ fast rise, spectral change
  ➤ slow rise, no spectral change

<table>
<thead>
<tr>
<th>Flare 1</th>
<th>Flare 2</th>
<th>Flare 3</th>
<th>Flare 4</th>
<th>Flare 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ=0.15</td>
<td>τ=0.83</td>
<td>τ=0.28</td>
<td>τ=0.13</td>
<td>τ=0.63</td>
</tr>
</tbody>
</table>
Offstates

![Graph showing countrate and hardness ratio over time]

- **Countrate (counts/s)**: 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50
- **Hardness Ratio**: 0.65, 0.70, 0.75, 0.80, 0.85
- **Dates**: 2003 November 20, 21, 22, 23, 24, 25, 26, November 27, 28, 29, 30, December 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

- **Flares**: Flare 1, Flare 2, Flare 3, Flare 4, Flare 5
- **Revs**: Rev 137, Rev 138, Rev 139, Rev 140, Rev 141

**Legend**:
- Red line: Countrate
- Blue line: Hardness Ratio

**Notes**:
- The graph shows a significant increase in countrate during Flare 1.
- The hardness ratio decreases during Flare 2.
Offstates
Offstates

- quasi periodic behavior
- Period: 6820 sec
Offstates

- quasi periodic behavior
- Period: 6820 sec
- flux decreases to zero
• 5 offstates detected
• no residual flux detectable
• countrate drops / increases extremely rapidly
• increase within 20 sec from 0 to ~100 cts/sec
• duration 500 - 2000 sec
• similar to previous offstates, but observed in detail
Discussion

- wind in a HMXB system very complex (X-ray photoionization...)
- time dependence (CAK wind model not sufficient)
  ➡ need 2D/3D simulations
  - short flares: highly variable density/velocity structure
    - shock fronts, dense filaments, accretion stream oscillates: flip-flop instability
    - predicted time scales: flares \( \sim 45\text{min} \) (flares 2,3,4)!

Taam & Fryxell (1989)
Discussion

- wind in a HMXB system very complex (X-ray photoionization...)
- time dependence (CAK wind model not sufficient)

➡ need 2D/3D simulations

- short flares: highly variable density/velocity structure
- shock fronts, dense filaments, accretion stream oscillates: flip-flop instability
- predicted time scales: flares \( \sim 45 \text{min} \) (flares 2,3,4)!
Discussion
Discussion

- no structured wind necessary so far:

→ presence of NS causes structure
no structured wind necessary so far:

presence of NS causes structure
• no structured wind necessary so far:

  ➡ presence of NS causes structure

• **BUT:** long flares 1 & 5: can **not** be explained by flip-flop instability

  ➡ blobs (or clumps) in the stellar wind

  But: flares quite long and Blobs very fast!

  significant fraction of binary orbit

• blob is viscously smeared out in accretion disk
Discussion

• no structured wind necessary so far:
  ➡ presence of NS causes structure

• BUT: long flares 1 & 5: can not be explained by flip-flop instability
  ➡ blobs (or clumps) in the stellar wind
  But: flares quite long and Blobs very fast!
  significant fraction of binary orbit

• blob is viscously smeared out in accretion disk
  ➡ can feed NS for several hours (flares 1 & 5)
Discussion

Offstates:

- absorption impossible
- not only blobs but also holes in stellar wind!
- density drops by factor $10^5$

Runacres & Owocki (2005)
SFXTs

- drop in acc. rate
- why no pulsations? why so sudden?
  ➞ onset of propeller effect?
- calculate flux for onset of propeller:

\[ F_X = 4.3 \times 10^{-7} \times \left( \frac{B}{10^{12}} \right)^2 \times P^{-7/3} \times \left( \frac{d}{1 \text{kpc}} \right)^{-2} \times \left( \frac{M}{1.4M_\odot} \right)^{-2/3} \]

\[ F_X = 1.1 \times 10^{-12} \text{ erg cm}^{-2}\text{s}^{-1} \rightarrow 10^{33} \text{ erg s}^{-1} \]

→ very close to what is observed for Vela X-1!
SFXTs

- drop in acc. rate
- why no pulsations? why so sudden?
- onset of propeller effect?
- calculate flux for onset of propeller:

\[ F_X = 4.3 \times 10^{-7} \times \left( \frac{B}{10^{12}} \right)^2 \times P^{-7/3} \times \left( \frac{d}{1\text{ kpc}} \right)^{-2} \times \left( \frac{M}{1.4M_\odot} \right)^{-2/3} \]

\[ F_X = 1.1 \times 10^{-12} \text{ erg cm}^{-2}\text{s}^{-1} \rightarrow 10^{33} \text{ erg s}^{-1} \]

- very close to what is observed for Vela X-1!

Vela X-1 enters region of low density \(\rightarrow\) propeller
SFXTs
SFXTs

- SFXTs (Supergiant Fast X-ray Transients)
- mostly below detection limit at > 20keV
- exhibit very short flares
SFXTs

• SFXTs (*Supergiant Fast X-ray Transients*)
• mostly below detection limit at > 20keV
• exhibit *very short flares*
• hardness ratio changes sometimes over flare
SFXTs

- SFXTs (Supergiant Fast X-ray Transients)
- mostly below detection limit at > 20keV
- exhibit very short flares
- hardness ratio changes sometimes over flare

Grebenev & Sunyaev (2007): SFXTs bright objects, but mostly in propeller regime
SFXTs

- SFXTs (Supergiant Fast X-ray Transients)
- mostly below detection limit at > 20keV
- exhibit very short flares
- hardness ratio changes sometimes over flare

Grebenkov & Sunyaev (2007): SFXTs bright objects, but mostly in propeller regime

Vela X-1 just opposite: rarely in propeller regime
Conclusions

• stellar wind in Vela X-1 is structured (clumps, holes)
• short and long flares up to 5.3 Crab
• Hardness ratio changes during rapidly rising flares ➞ also (sometimes) seen in SFXTs
• Offstates with no flux detected by ISGRI
• can be explained by triggering propeller effect
Conclusions

- stellar wind in Vela X-1 is **structured** (clumps, holes)
- **short** and **long** flares up to 5.3 Crab
- Hardness ratio changes during rapidly rising flares ➞ also (sometimes) seen in SFXTs
- **Offstates** with no flux detected by ISGRI
- can be explained by triggering **propeller** effect

➤ Vela X-1 is quite similar to SFXTs
Conclusions

- Stellar wind in Vela X-1 is **structured** (clumps, holes)
- **Short** and **long** flares up to 5.3 Crab
- Hardness ratio changes during rapidly rising flares ➔ also (sometimes) seen in SFXTs
- **Offstates** with no flux detected by ISGRI
- Can be explained by triggering **propeller** effect

➤ Vela X-1 is quite similar to SFXTs

Thank you for your attention!