Jet Propagation Through the Companion Wind

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What can we learn?

• Jet power
• Field topology
• Field strength (equipartition?)
• Composition
• How to heat spherical objects?
On its way out…

- Accretion flow
- Interstellar medium
  - diffuse
  - clouds
  - Stellar winds
- Companion wind
Cavities

Perseus (Fabian et al. 2008)
XRB Cavities:
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Gallo et al. 2005
Cyg X-1

[Graph and images related to Cygnus X-1]
Jet-bending:
\[ \psi_\infty = \frac{\dot{M}_{\text{wind}} v_{\text{wind}} v_{\text{jet}} h_1}{4\pi a L_{\text{jet,kin}}} \frac{\sqrt{\pi}}{2} \frac{\Gamma(3/2 - 1/\gamma)}{\Gamma(2 - 1/\gamma)} \]

Yoon & Heinz 2015, Yoon, Zdziarski, & Heinz 2016
Orbit + bending = Precession

- on orbital period
- opening angle $\psi_\infty$

$\Rightarrow$ Bending or precession constrain jet power
\[ L_{\text{jet}} \gtrsim 7.6 \times 10^{35} \text{ ergs s}^{-1} \]
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\[
\times \left( \frac{\dot{M}_{\text{wind}}}{2.6 \times 10^{-6} M_\odot \text{ yr}^{-1}} \right) \left( \frac{v_{\text{wind}}}{1.6 \times 10^8 \text{ cm s}^{-1}} \right) \left( \frac{v_{\text{jet}}}{0.6 c} \right) \left( \frac{\alpha_{\text{VLBA}}}{2^\circ} \right) \left( \frac{\sin \theta_{\text{LOS}}}{\sin 40^\circ} \right) \left[ \frac{f(\gamma)}{f(\gamma = 4/3)} \right] \left( \frac{z_{\text{VLBA}}}{a} \right)^{3/2(\gamma - 4/3)} ,
\]
Jet re-collimation shocks in stellar winds:

Figure 2. Left panel: Visualization of the P3e37 simulation. Red contour surface: section of the jet boundary; blue contour surface: section of the bow shock; yellow contour surface: surface of the star; bottom surface: slice through the temperature of the stellar wind and bow shock. Axes are in units of $10^{12}$ cm. Right panel: slice through P3e37 simulation at $z = 1.17 \times 10^{12}$ cm showing the structure of the bow shock and the formation of a weak surface shock on the leading edge of the jet; top panel: five pressure contours linearly spaced between 13% and 80% of the theoretical stagnation point pressure of the bow shock; overlayed in yellow is the approximate location of the contact discontinuity; bottom panel: 2D velocity streamlines in the x-y plane showing the deflection of the wind in the bow shock and the acceleration of jet material away from the stagnation point behind the surface shock and in the expansion wave in the downstream region of the jet.

Figure 3. The density contour maps in x-z plane for the P1e37 (left), P3e37 (middle) and P1e38 (right) models. The P1e37 model is from YH15, in which the considered length along the jet is an order of magnitude smaller than that of the P3e37 and P1e38 models. The vertical line up from the black hole position is shown by yellow dashes. The thick yellow line represents the identified jet centre from simulations and the thick red line represents the analytic approximation to the jet trajectory.
Lateral jet ram pressure:

\[ p_{\perp,\text{jet}} = \frac{L_{\text{jet}}}{\pi z^2 v_j} \]

a) **Location of re-collimation shock** *independent* of opening angle

b) **No** decollimation shock above critical power

\[ L_{\text{crit}} = \frac{\dot{M}_w v_w v_j}{16} \left( \frac{1 + \cos \xi}{\sin \xi} \right)^2 \]
• Bending depends on jet radius $R$
• Jet radius evolves due to
  1) Ballistic expansion (inner jet)
  2) Pressure balance with bow shock (outer jet)
**Winds & Clumps**

**Observations:**
- Jet not disrupted
  - a) Wind mass-loss rate orders of magnitude lower
  - or
  - b) Jet power limit derived here applies
Conclusions:

- Jet-wind interaction provides new, independent tool to constrain jet power in HMXBs
- Cyg X-1: $W > 1 \times 10^{36}$ ergs/s
- Recollimation shocks only form below critical jet power
- Suggest site of gamma-ray emission
- Clumps complicate things, but results robust unless mass flow orders of magnitude reduced