Jets in high-mass microquasars

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Outline

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  – Numerical simulations of relativistic jets

• Simulations of jets in high-mass microquasars:
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    • 3D
    • What do we learn
  – 2. Long term evolution of microquasar jets

• Conclusions
Jets in microquasars

- ~15 sources with detected radio-jets (microquasars) in the galaxy.
  - < 10% of total X-ray binaries (Massi ’05, Ribó ’05).
- Are all radio-emitting X-ray binaries microquasars? (Fender ’04)
  - 43 REXBs: 8 HMXBs and 35 LMXBs (Ribó 2005).
- To which extent is this picture (on the left) exact?
  - Accretion process.
    - Continuous vs periodic ejection?
  - Ambient medium.
    - Strong winds, inhomogeneities...
- Numerical simulations of microquasar jets needed to get a better picture!
  - Morphology and dynamics, locations of particle acceleration, variability,..
  - Peter & Eichler ’95 (collimation).
Numerical simulations of relativistic jets

Relativistic hydrodynamics: SRHD equations

\[
\frac{\partial D}{\partial t} + \nabla \cdot (Dv) = 0 \quad \text{(mass conservation)}
\]

\[
\frac{\partial S}{\partial t} + \nabla \cdot (S \otimes v + p\mathbf{I}) = 0 \quad \text{(momentum conservation)}
\]

\[
\frac{\partial \tau}{\partial t} + \nabla \cdot (S - Dv) = 0 \quad \text{(energy conservation)}
\]

**STATE VECTOR**

\[U = (D, S^1, S^2, S^3, \tau)\]

**FLUX VECTORS**

\[F^i = (Dv^i, S^1v^i + \delta^{1i}, S^2v^i + \delta^{2i}, S^3v^i + \delta^{3i}, S^i - Dv^i)\]

**DEFINITIONS**

- \(D = \rho W\): relativistic rest-mass density.
- \(S = \rho h W^2 v\): relativistic momentum density.
- \(\tau = \rho h W^2 c^2 - p - \rho W c^2\): relativistic energy density.
- \(v\): fluid flow velocity.
- \(W = 1/\sqrt{1 - v^2/c^2}\): flow Lorentz factor.

**FLUID REST FRAME QUANTITIES**

- \(\rho\): proper rest-mass density.
- \(h = 1 + \varepsilon/c^2 + p/\rho c^2\): specific enthalpy.
- \(\varepsilon\): specific internal energy.
- \(p\): pressure.

**RELATIVISTIC EFFECTS**

- \(h \geq 1 (\varepsilon \geq c^2)\)
- \(W \geq 1 (v \to c)\)
Numerical simulations of relativistic jets

• Some things we learned from simulations of extragalactic jets:
    • bow-shock, cocoon (backflow), hot-spots…
    • Influence of jet composition, ambient medium…

    • helical instabilities, long term evolution…
Numerical simulations of relativistic jets

- Some things we learned from simulations of extragalactic jets:
    - Morphology, influence of poloidal and toroidal components on the dynamics…
    - Jet acceleration.

  - Jet structure and morphology in the parsec-scales.
  - Trailing components, pop-up components, recollimation shocks…

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries

Detected gamma-ray binaries have a massive companion

$R_{\text{orb}} \approx 2 \times 10^{12} \text{ cm}$
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 2D simulations

2D simulations: Perucho & Bosch-Ramon 2008

powerful jet (3 $10^{37}$ erg/s)

320x2400 cells
20x300 $R_j$
+extended grid
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 2D simulations

2D simulations: Perucho & Bosch-Ramon 2008

weak jet ($3 \times 10^{34}$ erg/s)

mild jet ($10^{36}$ erg/s)

1920x1600 cells
120x200 $R_j$
+extended grid
Simulations of jets in high-mass microquasars
Wind-jet interaction in massive X-ray binaries: 3D simulations

Numerical Setup

• **Ratpenat** is a 3D RHD code that combines MPI and OMP parallelization.

• The simulations have been performed in **Mare Nostrum** (Barcelona Supercomputing Centre):
  – Distributed in nodes with 4 processors each.

• 32 nodes (**128 processors**).
  – Total of **320x320x1280** cells.
    – Numerical box: 40x40x10 $R_j$ per node.
      • The jet is divided in slices along the axis.
      • Extended radial region makes it (100x100x10 $R_j$ per node).
    – Resolution: 4 cells per jet radius at injection in the central region plus total of 80 cells in the extended region (**320x320x40 cells per node**).
      • The effective resolution is 16 cells per jet radius, because the jet expands very fast from injection.

Perucho, Bosch-Ramon & Khangulyan 2010
Simulations of jets in high-mass microquasars
Wind-jet interaction in massive X-ray binaries: 3D simulations
Input data

<table>
<thead>
<tr>
<th></th>
<th>WIND</th>
<th>JET 1</th>
<th>JET 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (erg/s)</td>
<td></td>
<td>$10^{35}$</td>
<td>$10^{37}$</td>
</tr>
<tr>
<td>Velocity (cm/s)</td>
<td>$2 \times 10^8$</td>
<td>$1.7 \times 10^{10}$</td>
<td>$1.7 \times 10^{10}$</td>
</tr>
<tr>
<td>Density (g·cm$^{-3}$)</td>
<td>$2.8 \times 10^{-15}$</td>
<td>$0.088 \rho_w$</td>
<td>$8.8 \rho_w$</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>$10^4$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Mach number</td>
<td>220</td>
<td>16.6</td>
<td>16.6</td>
</tr>
<tr>
<td>Pressure (dyn·cm$^{-2}$)</td>
<td>$1.5 \times 10^{-3}$</td>
<td>7.1</td>
<td>$7.1 \times 10^3$</td>
</tr>
</tbody>
</table>

Perucho, Bosch-Ramon & Khangulyan 2010
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Hypotheses

• Hydrodynamic-cold flow – particle dominated.
  – reasonable at certain distances to the compact object \((B \parallel \alpha r^{-2})\) and taking dissipation into account. Excepting strong shocks.
  – \(T_j << m_p c^2 / k_B\)

• stellar wind from a massive O-type star \((dM/dt = 10^{-6} M_{\text{sun}} \text{ yr}^{-1})\).
  – continuous in the simulation time-scales (100 -1000s).
  – compact object at the same orbital position during the simulation time-scales (100-1000s vs \(T > 100,000\) s).
  – homogeneous (constant density up to \(R_{\text{orb}}\)).

Perucho, Bosch-Ramon & Khangulyan 2010
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 1 \( t = 977 \text{ s} \)

**Logarithm of rest-mass density. X cut**

**Logarithm of rest-mass density. Z cut**
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 1 \( t = 977 \) s

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Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 2 \( t = 192 \text{ s} \)
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 2 \( t = 192 \text{ s} \)

Perucho, Bosch-Ramon & Khangulyan 2010
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: What do we learn

• There are strong interactions in the evolution of jets in massive binaries:
  – Recollimation shocks within the cocoon, but also within the wind region. These shocks are generated in the binary region if (see Perucho & Bosch-Ramon 2008):

Jet-cocoon interaction

\[
T_{j,0} < 3 \times 10^{14} \cdot \left(\frac{L_j}{10^{36} \text{ erg s}^{-1}}\right) \cdot \left(\frac{3 \times 10^9 \text{ cm s}^{-1}}{V_{bs}}\right) \cdot \left(3 \times 10^{11} \text{ cm}\right)^2 \cdot \left(10^{-15} \text{ g cm}^{-3}\right) \cdot \left(\frac{\rho_{j,0}}{\rho_{c}}\right) \cdot K,
\]

Jet-wind interaction

\[
T_{j,0} < 3 \times 10^{13} \cdot \left(\frac{\rho_w}{2.8 \times 10^{-15} \text{ g cm}^{-3}}\right) \cdot \left(\frac{V_w}{2 \times 10^8 \text{ cm s}^{-1}}\right)^2 \cdot \left(10^{-15} \text{ g cm}^{-3}\right) \cdot \left(\frac{\rho_{j,0}}{\rho_{j,0}}\right) \cdot K,
\]

Fulfilled for supersonic, mildly relativistic jets.

• These strong shocks are candidate locations for particle acceleration and high-energy emission.
  – the emission of gamma-rays produced at such a site reduces the absorption by interaction with stellar photons.
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: What do we learn

– The position of the recollimation shock depends on the cocoon pressure (Falle 1991):
  \[ z_s \propto P_c^{-1/2}, \]

• From Scheck et al. (2002) and Perucho & Martí (2007):
  \[ v_{bs} \propto t^\alpha \]
  \[ P_c \propto t^{-1-\alpha/2}, \quad z_s \propto t^{1/2+\alpha/4} \quad \text{for a homogeneous ambient} \]
  \[ P_c \propto t^{-2}, \quad z_s \propto t \quad \text{for} \quad \rho_a \propto z^{-2} \]

• We can compute the time \((t_3)\) at which the recollimation shock will reach
  – With \(z = 2 \times 10^{12} \text{ cm}\)
  \[ z_s(t_2) = 1.1 \times 10^{12} \text{ cm} \quad t_2 \approx 210 \text{ s} \]
  for \(\rho_a \propto z^{-2}: \ t_3 \approx 2t_2 \approx 400 \text{ s}\)

• We compare this time with the time at which the recollimation shock will be determined by the pressure of the shocked wind:
  \[ P_w \approx 10^2 \text{ erg cm}^{-3} \]
  – With \(P_c \approx 10^3 \text{ erg cm}^{-3}\) at \(t_2 = 210 \text{ s}\)
  \[ t \approx \sqrt{P_{c,0}/P_w} \quad t_2 \approx 3t_2 \approx 2t_2 \]
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: What do we learn

- **Instabilities** develop in the outer layers and propagate to the whole jet (in the form of *surface or first body helical modes*) after the strong recollimation shock: This can **destroy the jet**.
  - Better observational resolution could show the effect of the wind in the jet.

- **Only powerful jets** \((P_j > 10^{37} \text{ erg/s})\) in massive binaries may be able to propagate collimated out of the binary region.

- **Frustrated jets** may not be observed in radio at large distances.

- The luminosity function derived by Grimm et al (2003) predicts 3 HMXBs with \(L_X=10^{35} \text{ erg/s}\).
  - Following Fender et al. (2005), such HMXB with a 10 \(M_{\odot}\) Black Hole, the jet could have a kinetic power between \(10^{35}\) and \(10^{38}\) erg/s.
  - We deduce that there is room for a few (~10) such sources, with \(L_X \leq 10^{35} \text{ erg/s}\), in our Galaxy.
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

• Bordas, Bosch-Ramon, Paredes, MP 2009. SEE TALK BY P. BORDAS.
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

- Bordas, Bosch-Ramon, Paredes, MP 2009. SEE TALK BY P. BORDAS.

\[ P_j = 1.0 \times 10^{37} \text{ erg/s} \]

\[ n = 0.1 \text{ cm}^{-3} \]

\[ n = 1.0 \text{ cm}^{-3} \]
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Bosch-Ramon, Perucho & Bordas, in preparation

3 scenarios ($P_k = 3.\times 10^{36}$ erg/s):
- Case 1: young MQ ($t < 1.\times 10^5$ yrs), inside the hot SNR.
- Case 2: older MQ ($t \approx 1.\times 10^5$ yrs), the jet has left the SNR and propagates in the wind-wind/ISM shock-ISM
- Case 3: Similar to case 2 ($t \approx 1.\times 10^6$ yrs), with a bow-shock generated by the propagation of the binary through the ISM. The shocked wind impacts the jet from the side. Slab jet.
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Case 1: young MQ (t<1.e5 yrs), inside the hot SNR.

Shocked wind $z<8.e18$ cm

The image shows a simulation of the long-term evolution of microquasar jets. The plots depict the log pressure and log proper rest-mass density at $t=9.e3$ yrs. The density values are given as $\rho=3.3e-26$ g/cm$^3$, $\rho=6.7e-24$ g/cm$^3$, and $\rho=1.67e-24$ g/cm$^3$. The shocked wind region is marked by $z<8.e18$ cm.
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Case 1: young MQ (t<1.e5 yrs), inside the hot SNR.

$t=9.e3$ yrs
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

- Case 2: older MQ (t~1.e5 yrs), the SNR has dissipated and the jet propagates in the wind-wind/ISM shock-ISM

\[ t = 9.8e3 \text{ yrs} \]

![Log Pressure](image1.png)

- Shocked wind
- Shocked ISM

![Log Proper Rest-Mass Density](image2.png)

- \( \rho = 6.7e^{-27} \text{ g/cm}^3 \)
- \( \rho = 1.67e^{-24} \text{ g/cm}^3 \)
- \( \rho = 1.1e^{-22} \text{ g/cm}^3 \)

ISM
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Case 2: older MQ (t~1.e5 yrs), the jet has left the SNR and propagates in the wind-wind/ISM shock-ISM

$t=9.8e3$ yrs
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Case 3: Similar to case 2 ($t \sim 1.06 \text{ yrs}$), with a bow-shock generated by the propagation of the O-star through the ISM. The shocked wind impacts the jet from the side. Slab jet.

$v = 6.67 \times 10^{-3} \text{ c}$

$\rho = 4 \times 10^{-28} \text{ g/cm}^3$

$t = 2.03 \text{ yrs}$

$v = -3.3 \times 10^{-3} \text{ c}$

$\rho = 1.6 \times 10^{-24} \text{ g/cm}^3$

$\rho = 1.6 \times 10^{-27} \text{ g/cm}^3$

$\rho = 1.6 \times 10^{-22} \text{ g/cm}^3$
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Case 3: Similar to case 2 (t~1.e6 yrs), with a bow-shock generated by the propagation of the O-star through the ISM. The shocked wind impacts the jet from the side. Slab jet.

$t=2.e3~\text{yrs}$
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets
Conclusions

• Simple numerical simulations give important information about:
  – Sites of high-energy emission.
  – Jet stability and propagation.
  – Hints for the lost jets in REXBs and radio-quite XBs.
  – Long-term evolution and interaction with the inhomogeneous ambient.

• Further work:
  – Realistic scenarios:
    • expansion of the jet in decreasing density wind at larger scales + growing instabilities (now calculating for $P_j = 10^{37}$ erg/s). DONE.
    • Direct impact of the wind onto the jet when the head of the jet is far.
    • Effect of non-homogeneous wind. ONGOING.
  – Improved physics:
    • RMHD simulations, eos…
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Inhomogeneous wind