

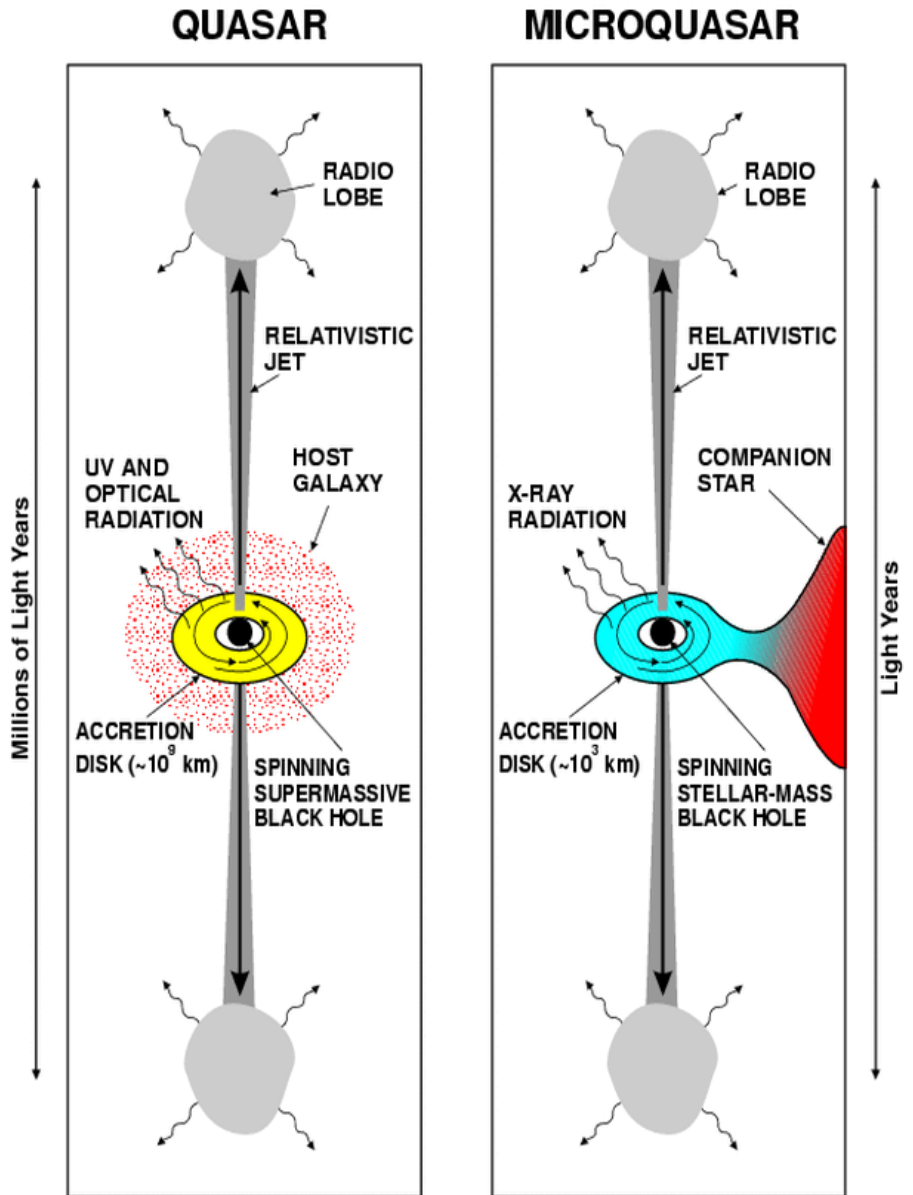
3D simulations of wind-jet interaction in massive X-ray binaries



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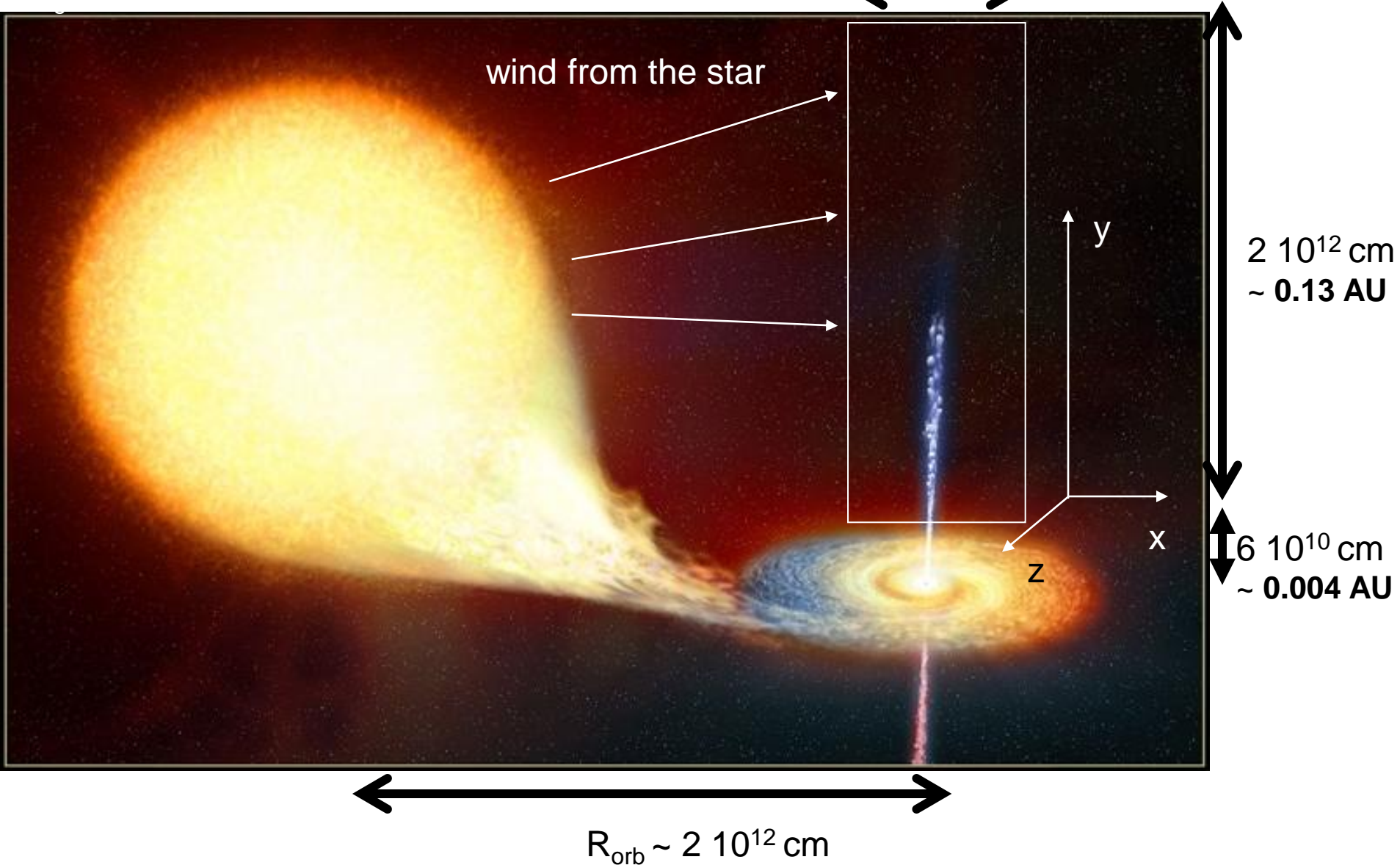
Jets in microquasars



- ~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).

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries
Detected gamma-ray binaries have a massive companion



Numerical simulations of relativistic jets

Relativistic hydrodynamics: SRHD equations

$$\frac{\partial D}{\partial t} + \nabla \cdot (D\mathbf{v}) = 0 \quad (\text{mass conservation})$$

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

$$\frac{\partial \tau}{\partial t} + \nabla \cdot (\mathbf{S} - D\mathbf{v}) = 0 \quad (\text{energy conservation})$$

STATE VECTOR

$$\mathbf{U} = (D, S^1, S^2, S^3, \tau)$$

FLUX VECTORS

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

DEFINITIONS

$D = \rho W$: relativistic rest-mass density.

$\mathbf{S} = \rho h W^2 \mathbf{v}$: relativistic momentum density.

$\tau = \rho h W^2 c^2 - p - \rho W c^2$: relativistic energy density.

\mathbf{v} : fluid flow velocity.

$W = 1/\sqrt{1 - \mathbf{v}^2/c^2}$: flow Lorentz factor.

FLUID REST FRAME QUANTITIES

ρ : proper rest-mass density.

$h = 1 + \varepsilon/c^2 + p/\rho c^2$: specific enthalpy.

ε : specific internal energy.

p : pressure.

RELATIVISTIC EFFECTS

$$h \geq 1 \quad (\varepsilon \geq c^2)$$

$$W \geq 1 \quad (v \rightarrow c)$$

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

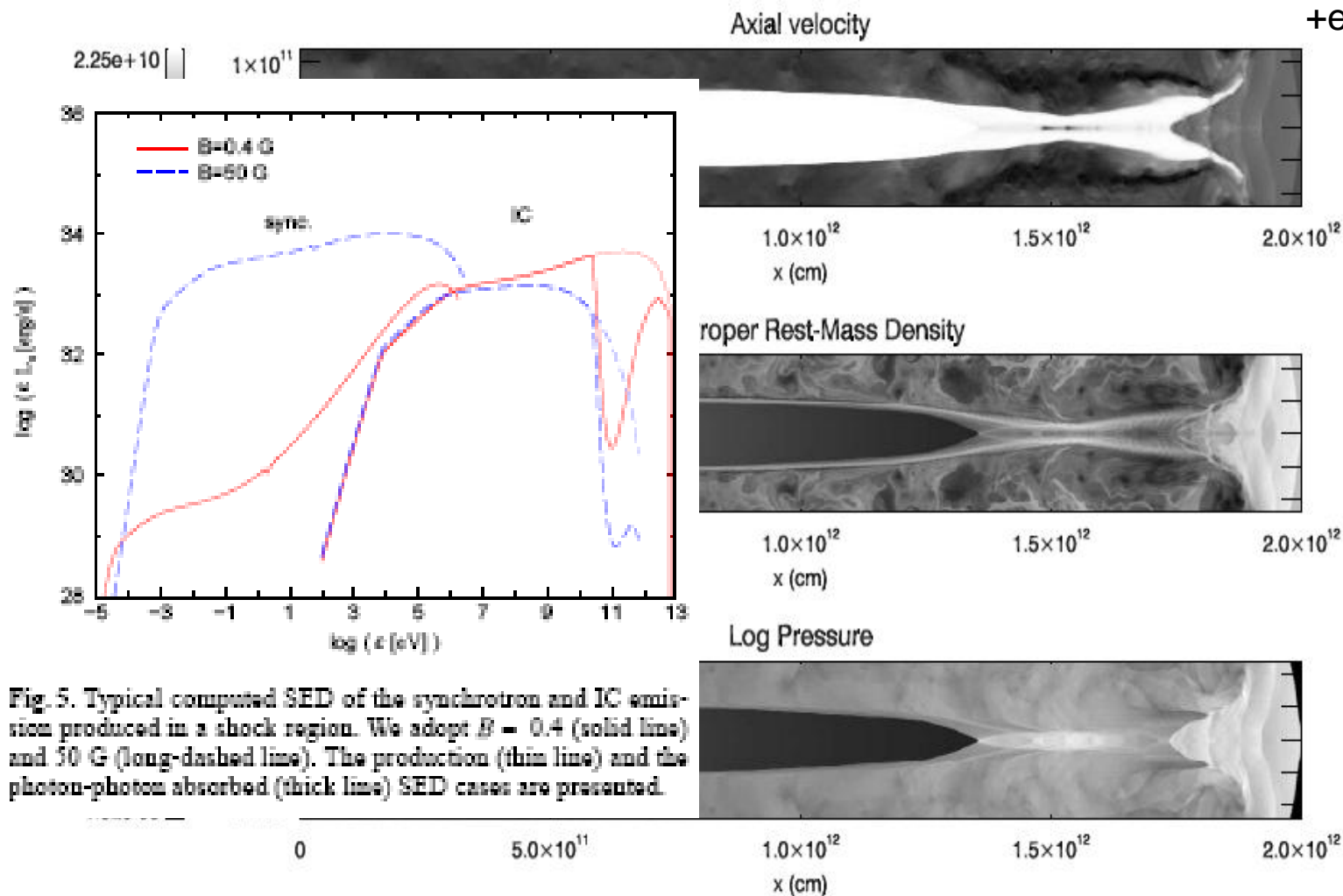


Fig. 5. Typical computed SED of the synchrotron and IC emission produced in a shock region. We adopt $B = 0.4$ (solid line) and 50 G (long-dashed line). The production (thin line) and the photon-photon absorbed (thick line) SED cases are presented.

Simulations of jets in high-mass microquasars

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

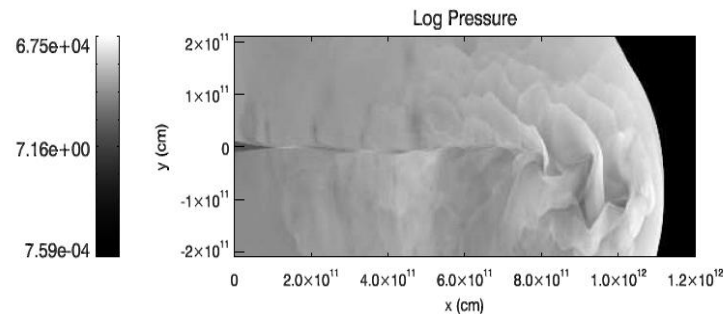
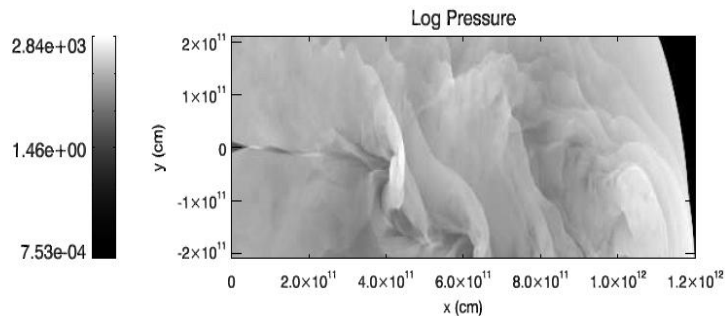
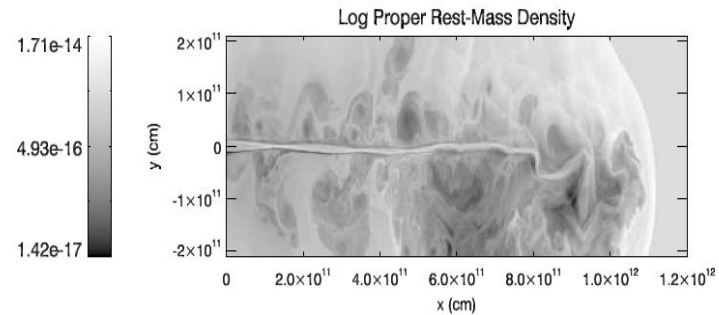
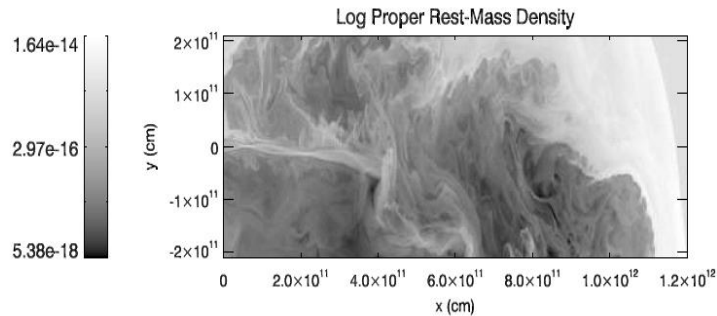
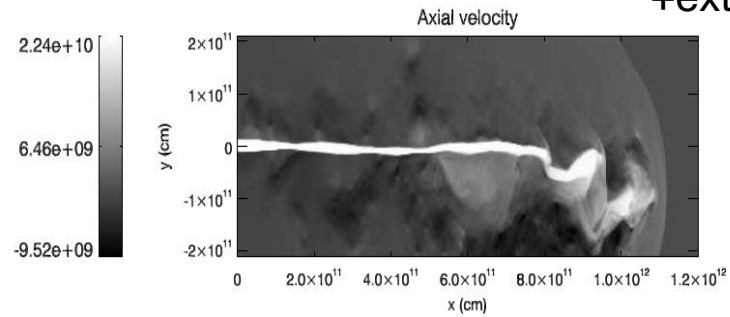
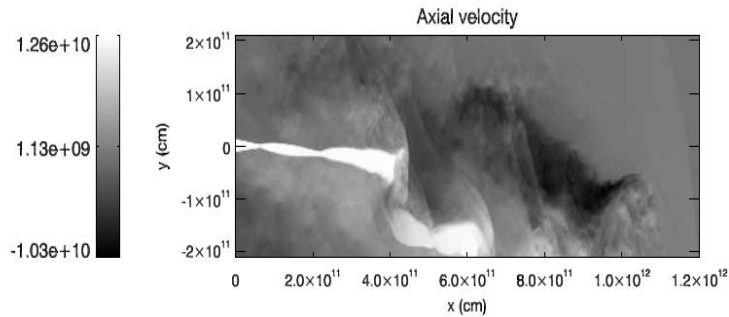
2D simulations: Perucho & Bosch-Ramon 2008

1920x1600 cells

weak jet (3×10^{34} erg/s)

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

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**) to reach $2 \cdot 10^{12}$ cm.
 - Total of **320x320x1280** cells.
 - Numerical box: $40 \times 40 \times 10 R_j$ per node.
 - The jet is divided in slices along the axis.
 - Extended radial region makes it $(100 \times 100 \times 10 R_j)$ 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.

Simulations of jets in high-mass microquasars

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

Input data

	WIND	JET 1	JET 2
Power (erg/s)		10^{35}	10^{37}
Velocity (cm/s)	$2 \cdot 10^8$	$1.7 \cdot 10^{10}$	$1.7 \cdot 10^{10}$
Density ($\text{g}\cdot\text{cm}^{-3}$)	$2.8 \cdot 10^{-15}$	$0.088 \rho_w$	$8.8 \rho_w$
Temperature (K)	10^4	10^{10}	10^{10}
Mach number	220	16.6	16.6
Pressure ($\text{dyn}\cdot\text{cm}^{-2}$)	$1.5 \cdot 10^{-3}$	7.1	$7.1 \cdot 10^3$

Simulations of jets in high-mass microquasars

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

Hypotheses

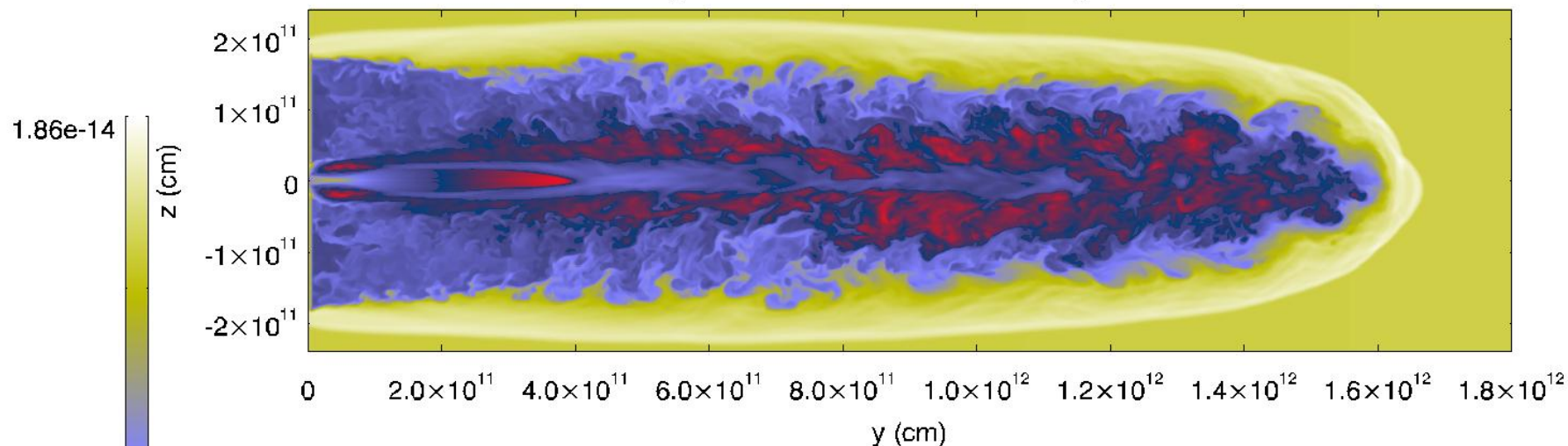
- **Hydrodynamic-cold flow – particle dominated.**
 - reasonable at certain distances to the compact object ($B_{\parallel} \propto r^{-2}$) and taking dissipation into account. Excepting at strong shocks.
 - $T_j \ll m_p c^2 / k_B$
- **stellar wind from a massive O-type star** ($dM/dt = 10^{-6} M_{\text{sun}} \text{yr}^{-1}$).
 - **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_{orb}).

Simulations of jets in high-mass microquasars

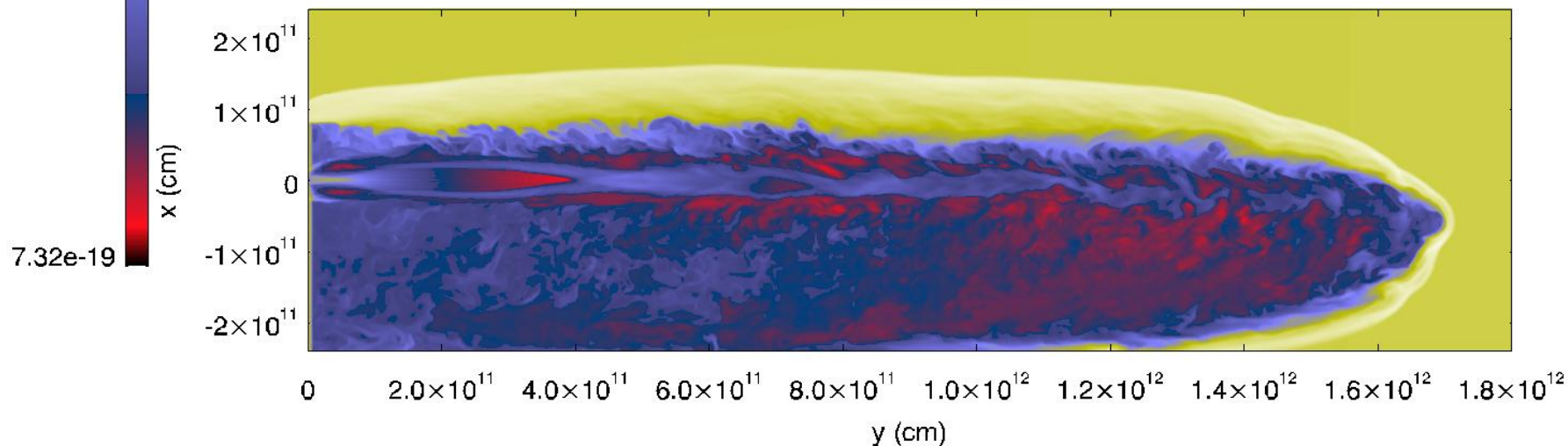
Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 1 $t = 977$ s

Logarithm of rest-mass density. X cut



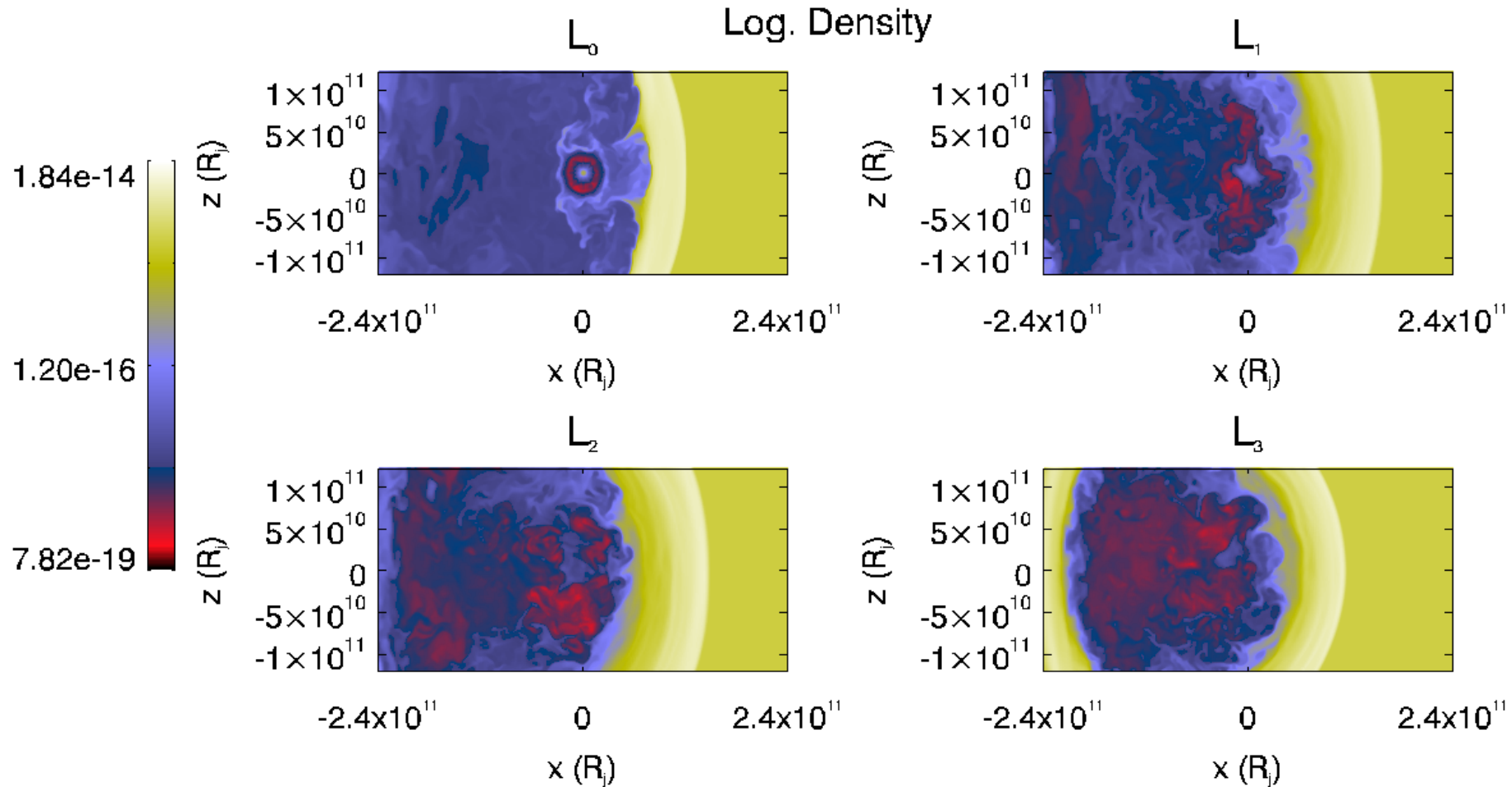
Logarithm of rest-mass density. Z cut



Simulations of jets in high-mass microquasars

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

Jet 1 $t = 977$ s

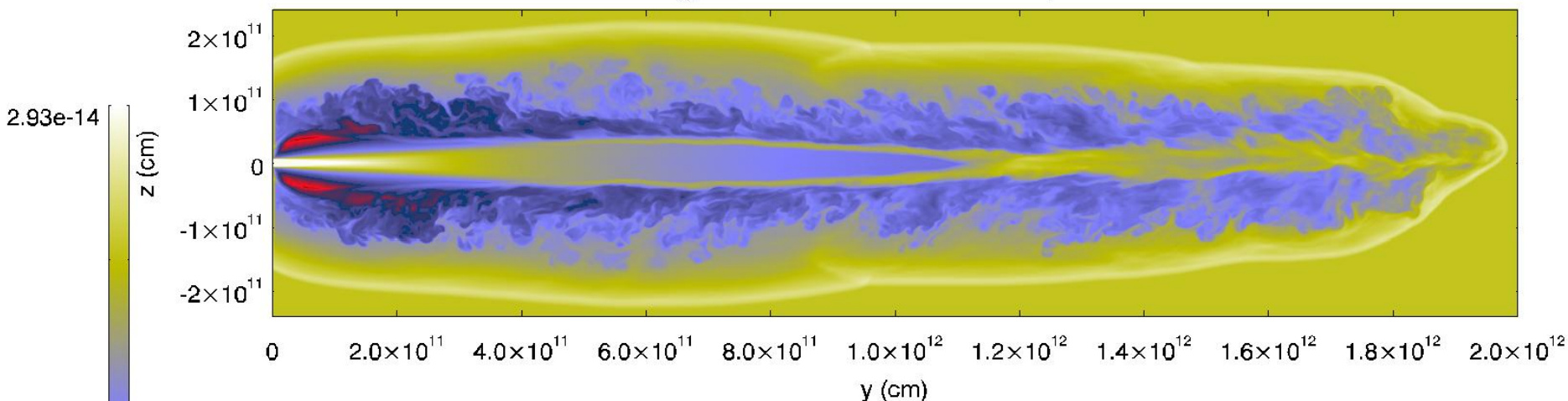


Simulations of jets in high-mass microquasars

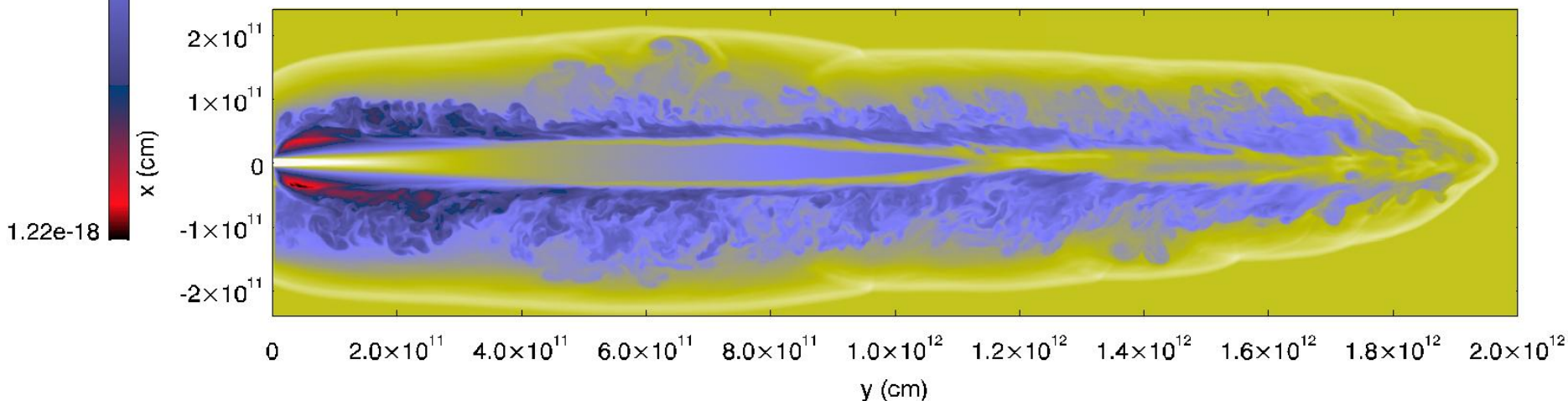
Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 2 $t = 192$ s

Logarithm of rest-mass density. X cut



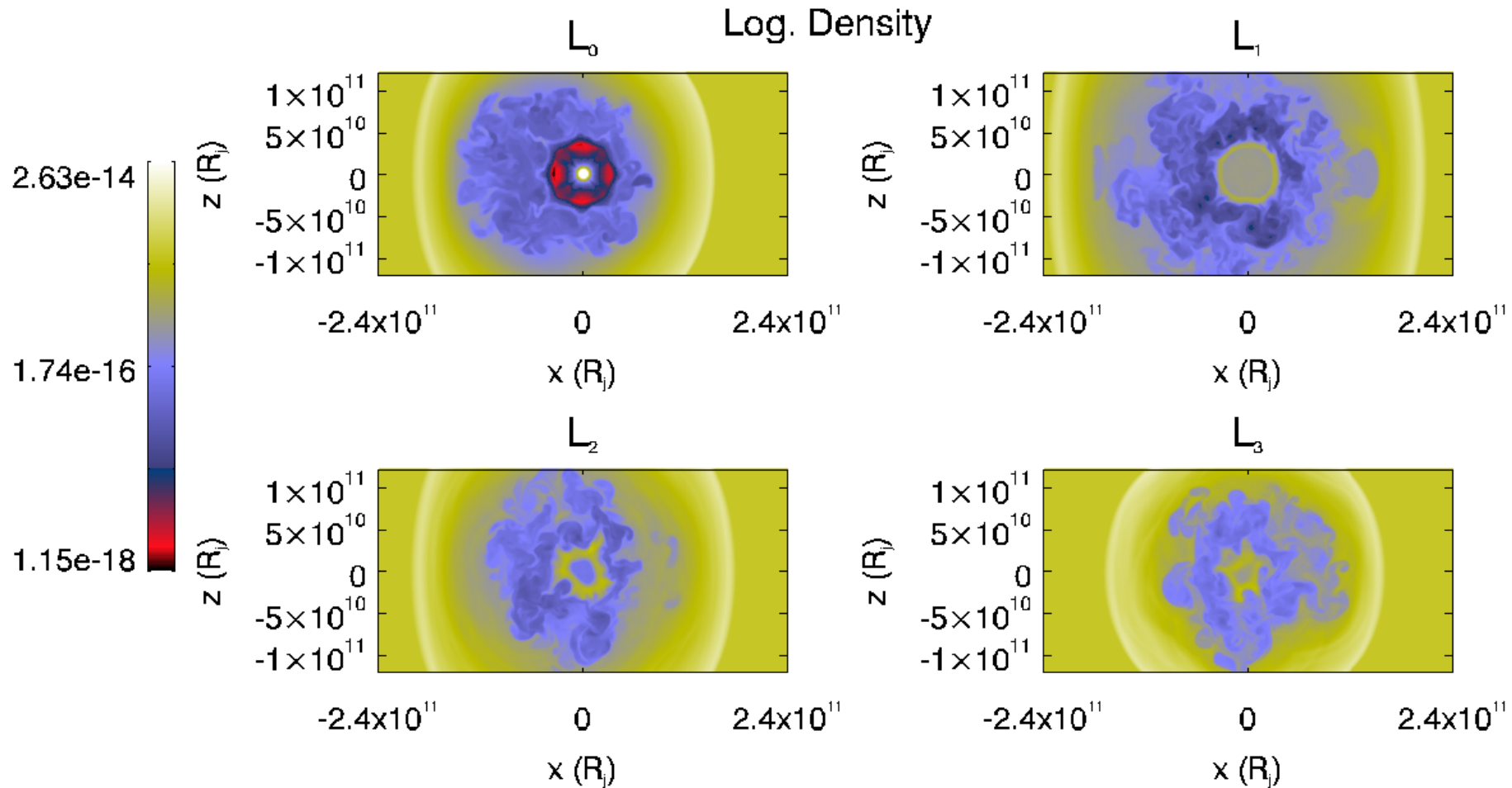
Logarithm of rest-mass density. Z cut



Simulations of jets in high-mass microquasars

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

Jet 2 $t = 192$ s



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

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

Jet-wind interaction

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

Fulfilled for supersonic, mildly relativistic jets.

Simulations of jets in high-mass microquasars

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

- 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.
 - Detected in several sources: LS5039 (Moldón et al. 2008, Hoffmann et al. 2009, Takahashi et al. 2009), Cygnus X-1 (Zdziarski et al. 2009, Sabatini et al. 2009) and Cygnus X-3 (Koljonen et al. 2010).

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): $v_{bs} \propto t^\alpha$

$$\begin{array}{ll} P_c \propto t^{-1-\alpha/2} & z_s \propto t^{1/2+\alpha/4} \quad \text{for a homogeneous ambient} \\ P_c \propto t^{-2} & z_s \propto t \quad \text{for } \rho_a \propto z^{-2} \end{array}$$

- We can compute the time (t_3) at which the recollimation shock will reach $z = 2 \times 10^{12}$ cm
 - With $z_s(t_2) = 1.1 \times 10^{12}$ cm and $t_2 \simeq 210$ s
- We compare this time with the time at which the recollimation shock will be determined by the pressure of the shocked wind: $P_w \sim 10^2 \text{ erg cm}^{-3}$
 - With $P_c \simeq 10^3 \text{ erg cm}^{-3}$ at $t_2 = 210$ s

$$t \simeq \sqrt{P_{c,0}/P_w} t_2 \simeq 3 t_2 \approx 2 t_2$$

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**.
 - Could be the case in the TeV X-ray binary LS 5039 (see Moldón et al. 2008 – arXiv:0812.0988 – and Ribó et al. 2008).
 - Better resolution could show the effect of the wind in the jet.
- **Only powerful jets** ($P_j > 10^{37}$ erg/s) in massive binaries may be able to propagate collimated out of the binary region.
- **Frustrated jets** may not be observed in radio.
- The luminosity function derived by Grimm et al (2003) predicts 3 HMXBs with $L_x = 10^{35}$ erg/s.
 - Following Fender et al. (2005), such HMXB with a $10 M_{\text{sun}}$ 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 $L_x \leq 10^{35}$ erg/s, in our Galaxy.**

Conclusions

- Our simple numerical simulations give important information about:
 - Candidate sites of **high-energy emission**.
 - **Jet** stability and **propagation**.
 - Hints for the **lost jets** in REXBs and radio-quiet 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. IN PROCESS.
 - Effect of **non-homogeneous wind**. IN PROCESS.
 - Improved physics:
 - **RMHD** simulations, **eos**...
 - Long-term evolution of microquasar jet (Bordas et al. 2009, Bosch-Ramon, Perucho & Bordas, in preparation):
 - **Interaction** with shocked wind, SNR, shocked ISM, ISM...