# Thermal radiative losses in high-mass microquasars jets

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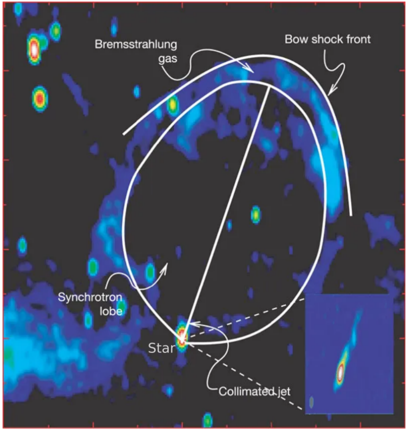
# HMMQ jets



Cygnus X-1 @1.4 GHz (Gallo *et al.* 2005)
Structure spans ∼15 ly

**Context:**
binary star systems
jet ($\beta \sim 0.1 - 0.9$) into stellar wind
emission from radio to gamma

**Aims:**
large scales ($\sim 10^{14}$ cm)
long times (quasi stationary state)
role of cooling and system parameters

**Methods:**
3D relativistic hydrodynamics
thermal radiative losses
AMR

**Challenge:**
months long simulation times

# Cygnus X-1 vs Cygnus X-3

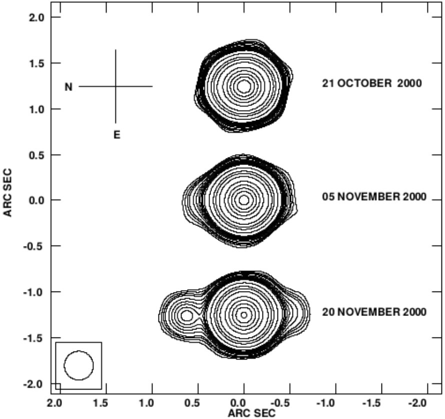
Parameters choice:

Cygnus X-1: Orosz *et al.* 2011, Yoon & Heinz 2015
Cygnus X-3: Zdziarski *et al.* 2013, Dubus *et al.* 2010

| | Cyg X-1 | Cyg X-3 | unit |
|---|---|---|---|
| star type | O9-B | WN 4-6 | |
| $M_{co}$ | 15 | $\lesssim 5$ | $M_\odot$ |
| $d_{orb}$ | $3 \cdot 10^{12}$ | $2.7 \cdot 10^{11}$ | cm |
| $\dot{M}$ | $3 \cdot 10^{-6}$ | $10^{-5}$ | $M_\odot$/yr |
| $v_w$ | 1000 | 1500 | km/s |
| $L_j$ | $5 \cdot 10^{36}$ | $10^{38}$ | erg $s^{-1}$ |
| $\beta_j$ | 0.33 | 0.75 | |

Cygnus X-3:

→ more compact system, stronger wind
→ hotter star, stronger $B$ field
→ denser, faster, more energetic jet
⇒ stronger losses expected



arcsecond radio jets in Cygnus X-3
(Marti *et al.* 2001)

# Code and physics

Simulations with A-MaZe toolkit (Walder & Folini 2000, 2003):

- finite volume method
- forward Euler scheme
- 2nd order Lax-Friedrich
- min-mod limiter

$\rho_j$, $v_j$, $T_j$ at injection
x=0 reflecting conditions
outflow elsewhere

Relativistic hydrodynamics:

$$\partial_t D + \partial_i (D v^i) = 0 \tag{1}$$

$$\partial_t S^j + \partial_i (S^j v^i + p c^2 \delta^{ij}) = 0 \tag{2}$$

$$\boxed{\partial_t \tau + \partial_i S^i = -P_{loss}} \tag{3}$$

coarse grid: $250 \times 200 \times 200$ cells
$\sim 7 \times 5 \times 5$ AU
$dx = dy = dz = 4 \cdot 10^{11}$ cm

fixed grid centered on jet for performance
5 levels up to ×64 refinement where jet is launched

Relativistic solver with recovery of primitive variables

First simulations including relativistic hydrodynamics *and* large scales
First implementation of radiative loss effects in jet dynamics

# Radiative losses

free-free + relativistic correction (Rybicki & Lightman 1979):

$$P_{ff} \propto \rho^2 T^{1/2} g_{ff}(T)(1 + \frac{T}{10^{10}\ \mathrm{K}}) \qquad (4)$$

$g_{ff}$ frequency-averaged Gaunt factor

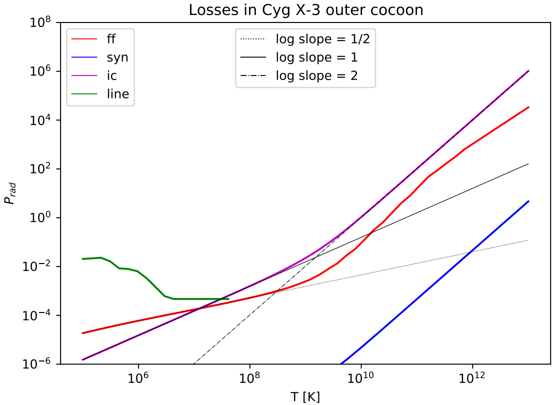
- $g_{ff} = 1.2$ in CygX1 runs
- $g_{ff}(T)$, van Hoof *et al.* 2015 for CygX3

synchrotron and inverse Compton derived from Maxwell-Jüttner for $e^-$:

$$P_{syn,\ IC} \propto \gamma \rho T \frac{K_3}{K_2}\left(T^{-1}\right) U_{B,\ rad} \qquad (5)$$

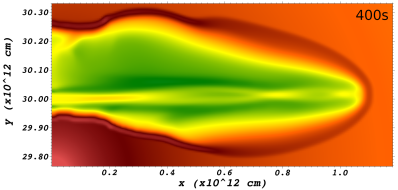
line recombination, Cook *et al.* 89:

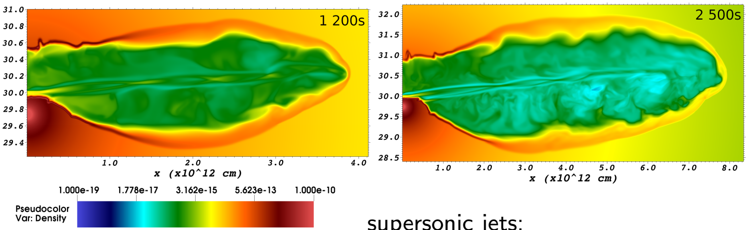
$$P_{line} \propto \rho^2 \Lambda(T) T^{\beta(T)}, \ \ T < 10^{7.7}\ \mathrm{K} \qquad (6)$$

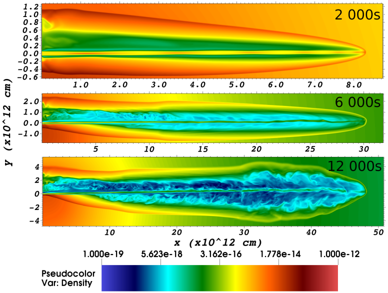


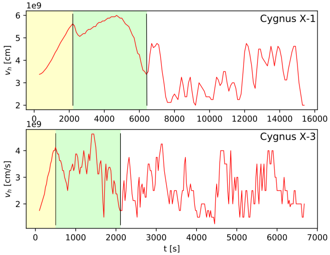
$P_{rad}(T)$ for typical CygX3 cocoon values, $\rho = 10^{-14}$ g cm$^{-3}$, $\gamma = 1$

# Fiducial runs









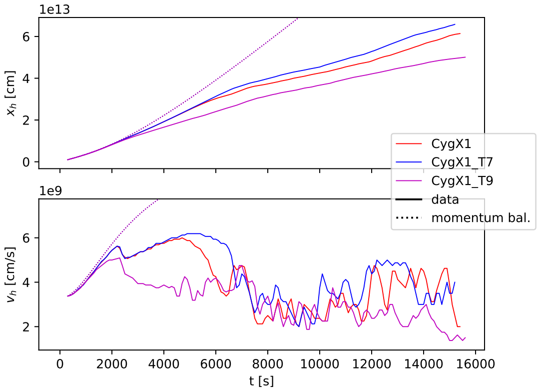
supersonic jets:

- →beam, inner cocoon, outer cocoon
- →KHI dominated
- →3 phases

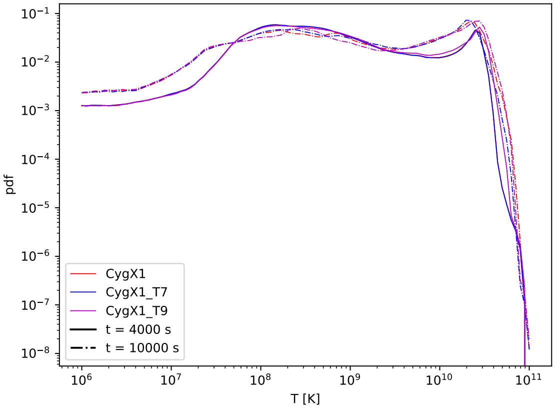
KHI development

- →beam internal shocks
- →head oscillation
- →mixing

# Parametric study

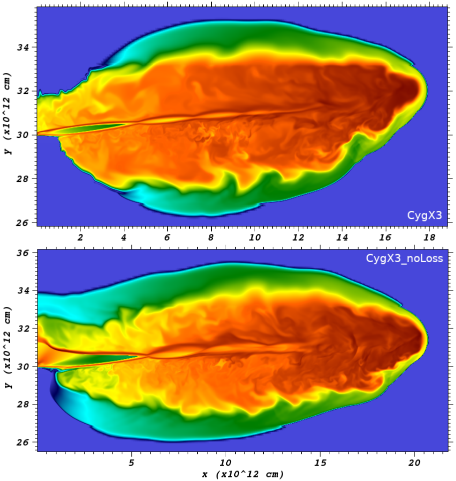


→ beam temperature matters for stability
→ threshold at $10^9$ K



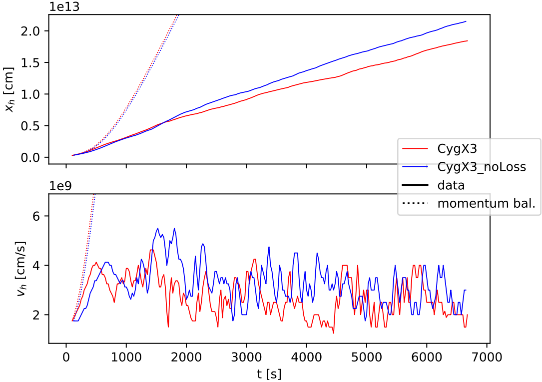
two temperature peaks ←
consequences on emission ←

# Cooled vs adiabatic

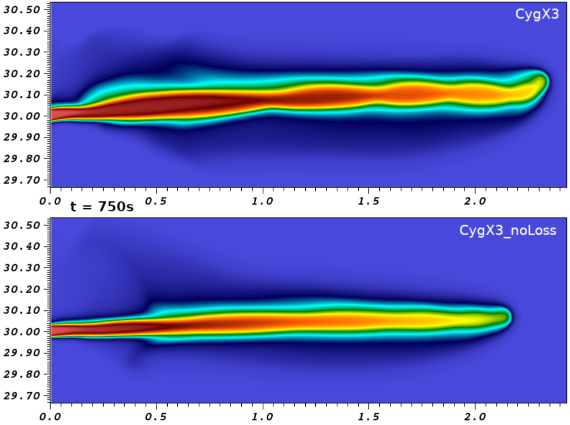


Temperature slices ($10^6$ to $10^{13}$ K), t = 6250s

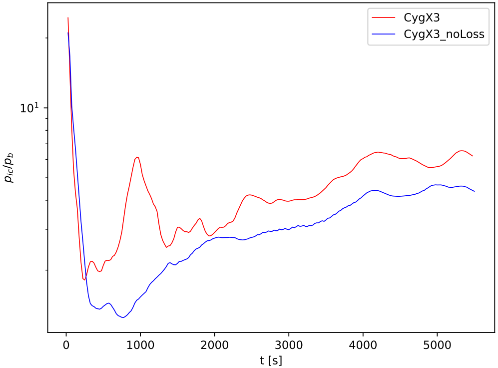
Cygnus X-1: $t_{cool} > t_{dyn}$, barely any effects
Cygnus X-3: $t_{cool} < t_{dyn}$
→ focus on Cygnus X-3 case



# Cooled vs adiabatic (2)



Tracer density



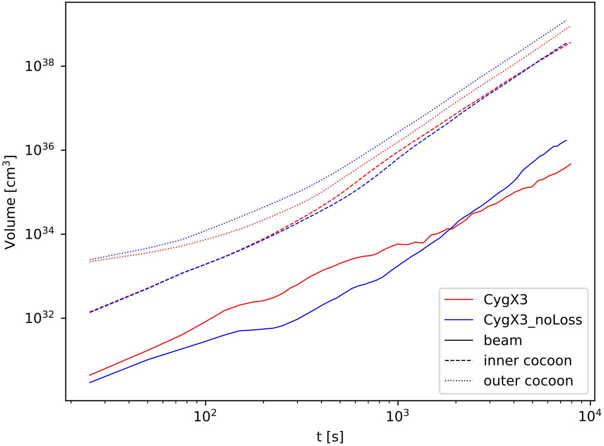
inner cocoon/beam pressure ratio

higher overpressure in cooled jet

→ stronger oblique shocks

→ faster KHI growth

# Cooled vs adiabatic (3)



→ expansion becomes self-similar

<u>outer cocoon:</u>
  → smaller in cooled jet but same law
<u>inner cocoon:</u>
  → slightly stronger slope for non-cooled jet
<u>beam:</u>
  → strong difference in behaviour

# Conclusions and prospects

## Conclusions

- First large scale relativistic study of cooling in HMMQ jet outbreaks
- Weak to no effects on Cygnus X-1, structural and dynamical modifications for Cygnus X-3
- Parameter dependence of quantities (e.g. temperature pdf, self-similarity power laws...)

(paper to be submitted : A. Charlet et al. 2021)

## Prospects

- Study steady-state structure
- Compute synthetic thermal and non-thermal emission spectra