Dynamical effects of radiative losses in high-mass microquasars

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Outline

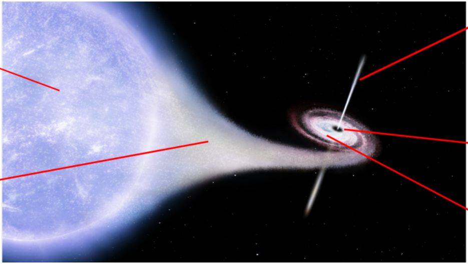
Plan

High Mass Microquasars

Lab of relativistic plasma physics:

Star

Mass transfer
winds + Roche lobe



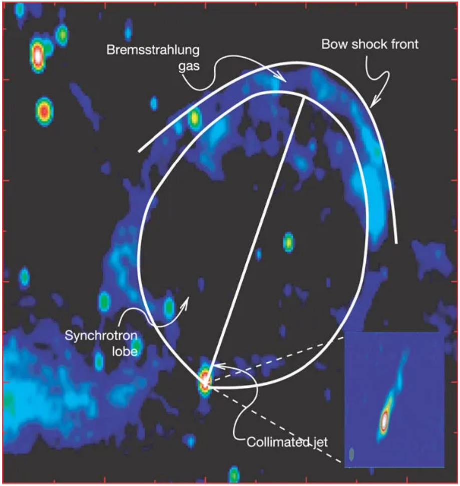
Jets
relativistic colisionless plasma
thermal and non-T particles
wind influence
radio & X-Ray radiation source
particle acceleration: CR source ?

Black Hole
general relativity + MHD
accretion, jet launch

Disk
resistive MHD
accretion regimes, link with jet launch

2 main spectral states:
Low Hard State (LHS): peak $\sim$ 100 keV + radio jets (Corbel *et al.* 2012)
High Soft State (HSS): black body-like peak 1 keV

Observed jets



large-scale structure
Different zones = different radiative processes

Collimated jet misaligned with structure: are we sure it originates from the jet ?

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

Motivations

Questions:

- jet contribution to HE spectrum ?
- dynamical effects of wind & radiative losses ?

Difficulties:

- midly relativistic regime: usual approximations not valid
- adding radiative processes = calculation time++

State of the art:

- no global simulations with dynamical losses

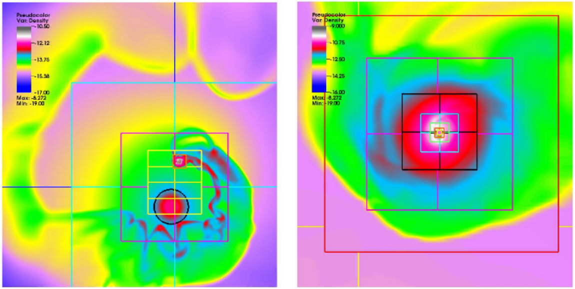
My work:

- calculation of radiative processes in our general regime
- RHD and radiative losses in A-MaZe
- global simulations over a long time period

Plan

Code

`A_MaZe` (R. Walder, D. Folini)



accretion in Cygnus X-1 (Walder et al. 2014)

- newtonian hydrodynamics
- conservative scheme
- finite volumes
- multiD *upwind* algorithm
- AMR

Box dimension 1AU (left), $\sim$ 0.01AU (right), refinement up to $8R_S$ (right)

Relativistic hydrodynamics

Primitive variables:		*Conservative variables:*
rest frame density	ρ	$D = \gamma\rho$
velocity	v^i	$S^i = cT^{0i} = \rho h \gamma^2 v^i$
pressure	p	$\tau = T^{00} - J^0 c^2 = \rho h \gamma^2 - p$

Conservation of current $J^\mu = \rho u^\mu$ and energy-momentum tensor $T^{\mu\nu} = \rho h u^\mu u^\nu + p g^{\mu\nu}$

$$\nabla_\mu J^\mu = 0 \quad \nabla_\mu T^{\mu\nu} = 0 \quad \Rightarrow$$

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

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

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

Radiative mechanism

$$P_{loss} = P_{Bremsstrahlung} + P_{Synchrotron} + P_{InverseCompton}$$

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Bremsstrahlung + relativistic correction (Rybicki & Lightman 1979):

$$P_{Bremsstrahlung} = 1.4 \cdot 10^{-27} T^{1/2} n_e n_p \bar{g}_B (1 + 4.4 \cdot 10^{-10} T) \quad (4)$$

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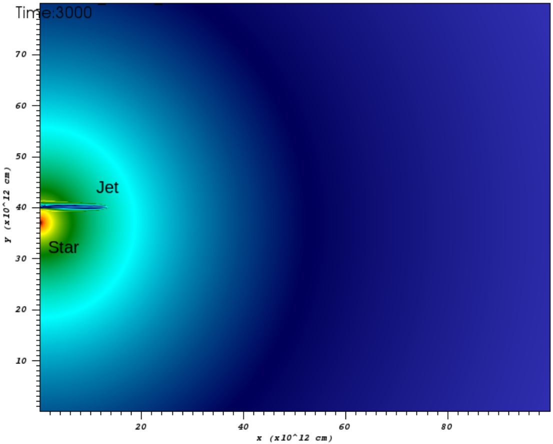
Synchrotron and IC: RL79 modified with relativistic Maxwellian distribution:

$$P = \frac{4}{3} \sigma_T c n_e \gamma^2 \beta^2 U \quad \Rightarrow \quad P = \frac{4}{3} \sigma_T c n_e \gamma \Theta \frac{K_3(1/\Theta)}{K_2(1/\Theta)} U$$

Plan

Large scale



full-size density map

Star - BH separation a = 0.2 AU

reflexive conditions at x=0, outflow elsewhere

ρ_j, v_j, T_j at injection

box $\sim 7 \times 5 \times 5$ AU

coarse grid: $250 \times 200 \times 200$,
$dx = dy = dz = 4 \cdot 10^9$m
5 levels up to $\times 64$ refinement
fixed grid centered on jet for performance

12 setups

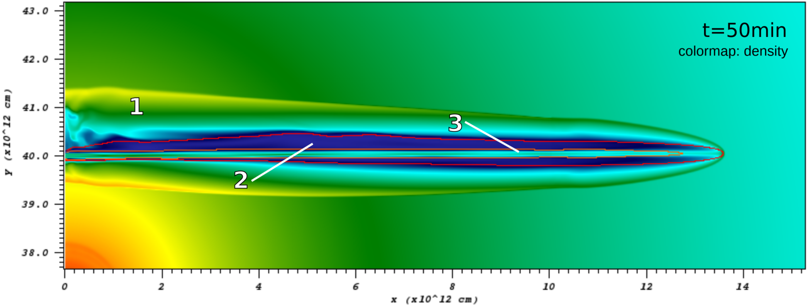
following figures all in log scale

Jet morphology

Cocoon (1): shocked wind material, **large emitting bubble**
Inner cocoon (2): jet + wind material, **instabilities**
Beam (3): injected matter, **recollimation shocks**

Here:
$10^{-17} < \rho < 10^{-13}$ g cm^{-3}
$10^{7} < T < 10^{11}$ K

Jet				Star			
P_j	ρ_j	v_j	r_0	$\dot{M}_\star$	v_w	$T_\star$	(cgs)
10^{37}	$1.3 \cdot 10^{-15}$	$1 \cdot 10^{10}$	$5 \cdot 10^{10}$	$3 \cdot 10^{-6}$	10^{8}	$3 \cdot 10^{4}$	



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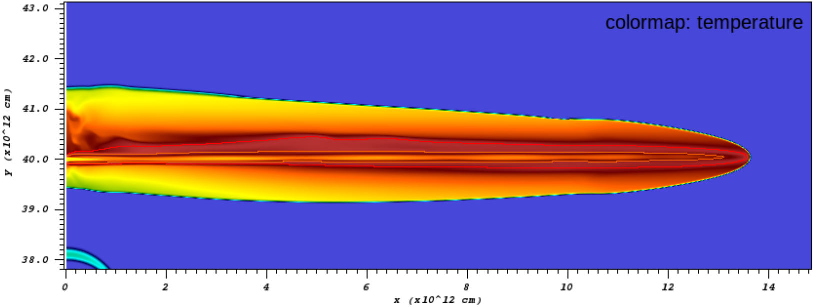
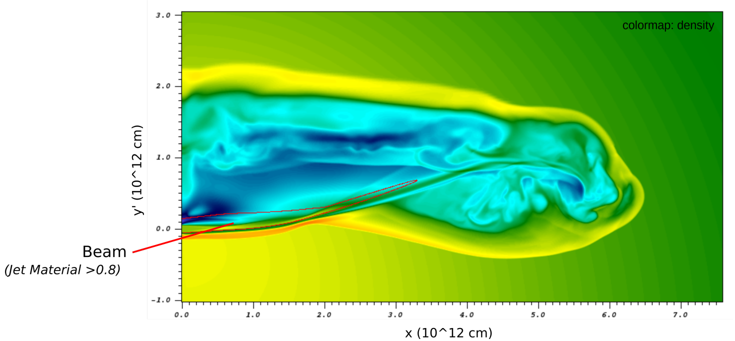


Jet bending

P_j	ρ_j	v_j	v_w
10^{36}	$4.72 \cdot 10^{-15}$	$3 \cdot 10^{9}$	$1.5 \cdot 10^{8}$

(cgs), t=1h40



$\mathbf{P_j} < \mathbf{P_{lim}}$, strong bending of the beam & instabilities (Molina & Bosch-Ramon 2018)

$\rightarrow$ misaligned large-scale structure of Cyg X-1 ?

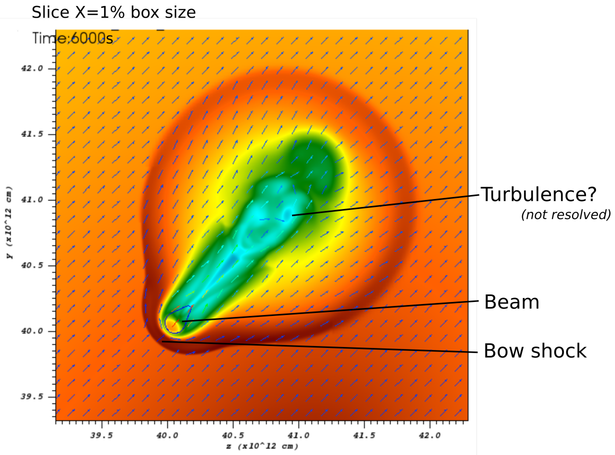
Cocoon deformation

P_j	ρ_j	v_j	v_w
10^{36}	$4.72 \cdot 10^{-15}$	$3 \cdot 10^9$	$1.5 \cdot 10^8$

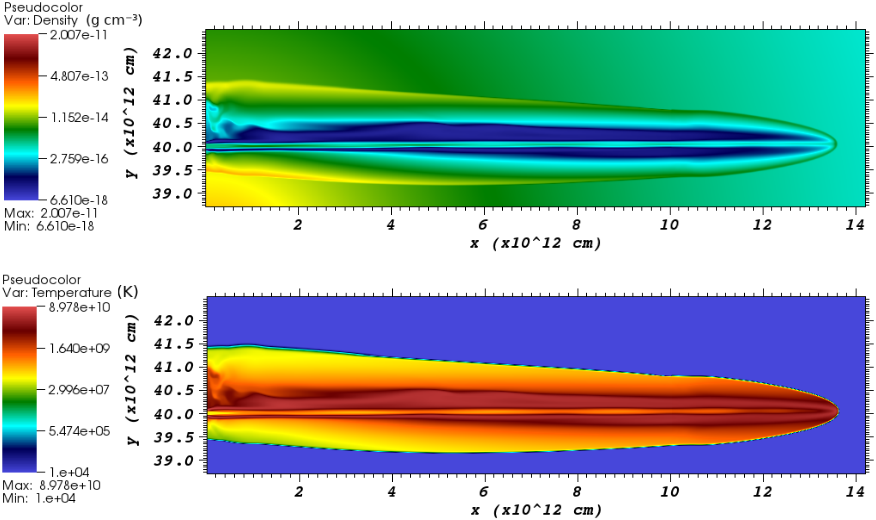
(cgs), t=1h40

Previous simulation sliced at x = a/3: strong stellar wind

Bow shock around beam, cocoon pushed by wind



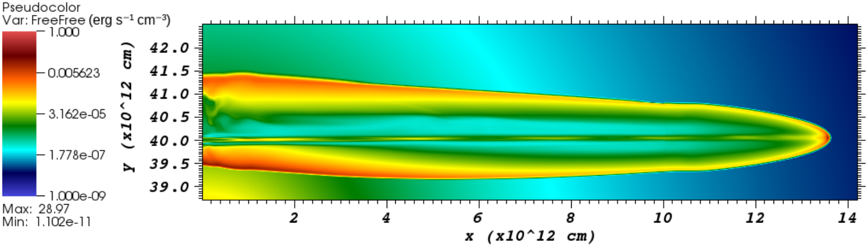
Maps



logscale maps of ρ and T

Bremsstrahlung

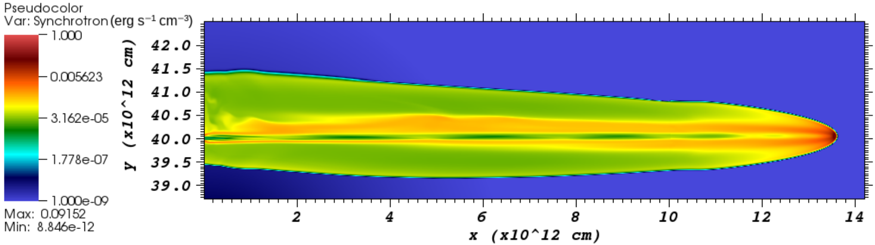
Jet			Star	
P_j	ρ_j	v_j	v_w	(cgs), t=50min
10^{37}	$1.3 \cdot 10^{-15}$	$1 \cdot 10^{10}$	10^8	



$\epsilon \propto \rho^2 T$, strong at front shock and cocoon interface

Synchrotron

Jet			Star	
P_j	ρ_j	v_j	v_w	(cgs), t=50 min
10^{37}	$1.3 \cdot 10^{-15}$	$1 \cdot 10^{10}$	10^8	

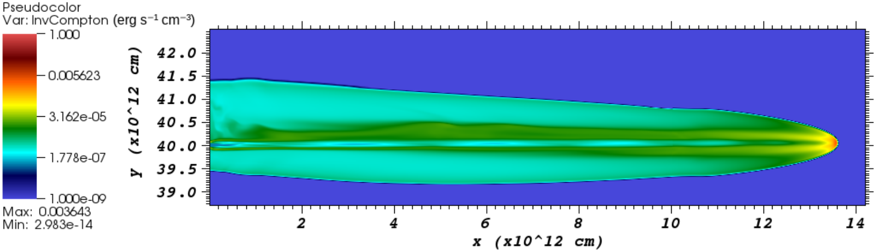


Strongest at shock front

$U = B^2/8\pi$, with $B_{\star,0} = B_{j,0} = 10$ G

Inverse Compton

Jet			Star	
P_j	ρ_j	v_j	v_w	(cgs), t=50 min
10^{37}	$1.3 \cdot 10^{-15}$	$1 \cdot 10^{10}$	10^8	

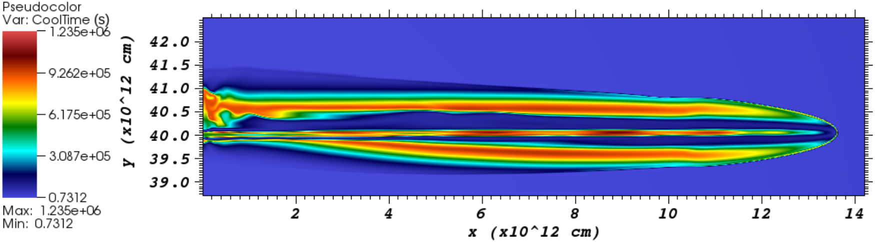


Same ρ, T dependance as synchrotron $\rightarrow$ same structure, overally weaker
$U \propto \sigma_T T_\star^4$

Cooling time

$t_{cool} = e_{int}/\Sigma\epsilon_i$

Jet			Star	
P_j	ρ_j	v_j	v_w	(cgs), t=50 min
10^{37}	$1.3 \cdot 10^{-15}$	$1 \cdot 10^{10}$	10^8	



low t_{cool} near beam injection (stronger winds) and inner cocoon
high t_{cool} for beam

Conclusions and prospects

Conclusions

implementation of SR hydro with radiative losses in `A_MaZe`

jet bending under critical P_j and cocoon deformation

high t_{cool} variability: modified structure but no effects on propagation (yet)

Prospects

refine the model:
- $T > 10^{10}$ K ($e^{\pm}$ production), adapt the EoS
- add non-thermal e^{-} $\rightarrow$ modifications to the dynamics ?

launch a simulation at best precision

draw radiation maps (radio/UV/X) and spectras

simulate other systems