High-energy emission from microquasar jet-clumpy stellar wind interactions

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Outline

1. Introduction
2. Model of the jet/clump interaction
3. Application of the model
4. Conclusions

Motivation

- HMMQs are formed by a compact object and a donor massive early-type star. They present relativistic jets.
- Strong observational evidence suggests that stellar winds of massive stars are clumpy (Owocki & Cohen 2006).
- The interaction of these inhomogeneities (clumps) with the MQ jet may lead to flaring activity (Owocki et al. 2009).
- Very high-energy flares could have been detected from Cygnus X-1, LS I +61 303, LS 5039 (Paredes 2009, and references therein) and Cygnus X-3 (Tavani et al. 2009, Abdo et al. 2010).

The microquasar scenario

We assume a supersonic and hydrodynamical jet...

- Height/width relation:
  $r_{\mathrm{j}} = 0.1\, z_{\mathrm{j}}$

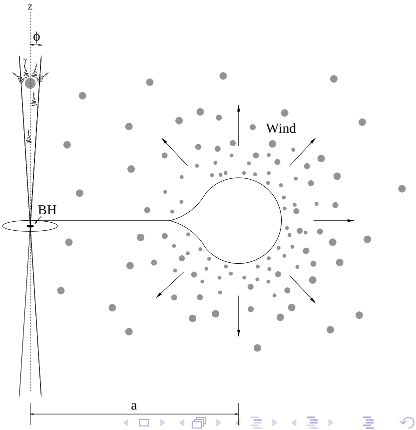
...and a clumpy wind with a filling factor f.

Clumps parameters:

- Radius: $R_{\mathrm{c}} = 0.1 - 0.01\, R_{\star}$
- Density: $\rho_{\mathrm{c}} = \rho_{\mathrm{wind}}/f$
- Velocity: $v_{\mathrm{c}} = v_{\mathrm{wind}}$

An important parameter:

$\chi \equiv \frac{\rho_{\mathrm{c}}}{\rho_{\mathrm{j}}(\Gamma_{\mathrm{j}}-1)}$

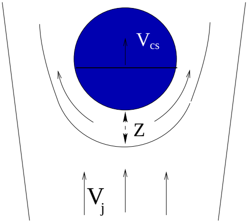


Relevant dynamical timescales (I)

- Clump/jet penetration time: $t_{\rm c} \sim \frac{2\,R_{\rm c}}{v_{\rm c}}$
- Jet crossing time: $t_{\rm j} \sim \frac{2\,R_{\rm j}}{v_{\rm c}}$

Two shocks are formed:

- Clump shock crossing time: $t_{\rm sc} \sim \frac{2\,R_{\rm c}}{v_{\rm sc}}$, $\quad v_{\rm sc} = \frac{v_{\rm j}}{\sqrt{\chi}}$
- Bow-shock formation time: $t_{\rm bs} \sim \frac{Z}{v_{\rm bs}} \sim \frac{0.2\,R_{\rm c}}{v_{\rm j}}$



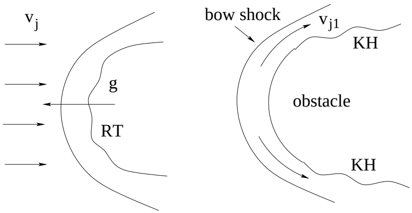
Relevant dynamical timescales (II)

The jet can accelerate the clump.

- Clump acceleration time: $t_{\rm c}^{\rm acc} \sim \frac{2\,R_{\rm c}}{g_{\rm j}} \sim \sqrt{\chi}\,t_{\rm sc}, \qquad g_{\rm j} \sim \frac{v_{\rm j}^2}{\chi R_{\rm c}}$.

Instabilities grows in the jet/clump contact surface.

- Rayleigh-Taylor and Kelvin-Helmholtz instabilities: $t_{\rm RT,KH} \sim t_{\rm sc}$.



Numerical simulations show that clump disruption needs several $t_{\rm sc}$ (Klein, McKee & Colella 1994)

Location of the accelerator / emitter

Interaction height: $t_{\rm sc} > t_{\rm c} \Rightarrow$
$z_{\rm int} > 7.3 \times$
$10^{10} \left(\frac{v_{\rm c}}{2000\,{\rm km\,s^{-1}}}\right)^{-1} \left(\frac{n_{\rm c}}{10^{13}\,{\rm cm^{-3}}}\right)^{-1/2} \left(\frac{v_{\rm j}}{c/3}\right)^{1/2} \left(\frac{L_{\rm j}}{10^{36}\,{\rm erg\,s^{-1}}}\right)^{1/2}$ cm

Bow shock: good place for particle acceleration.
$(L_{\rm sh} \propto v_{\rm sh}^3 \rightarrow L_{\rm bs}/L_{\rm sc} \propto \chi)$
Jet-shocked region + clump: emitters.

Injected relativistic particles: $Q_{e,p} = K_{e,p}\, E_{e,p}^{-2}$

Luminosity of relativistic particles: $L_{\rm nt} = \eta_{\rm nt} L_{\rm bs} = \eta_{\rm nt} \left(\frac{R_{\rm c}}{R_{\rm j}}\right)^2 L_{\rm j}$

Magnetic field: $U_{\rm B} = \eta_{\rm B} U_{\rm nt} = \eta_{\rm B} \frac{L_{\rm nt}}{\sigma_{\rm c}\, c} \rightarrow B = \sqrt{8\pi\, \eta_{\rm B} \frac{L_{\rm nt}}{\sigma_{\rm c}\, c}}$

Shocked jet and clump emission

Shocked jet emission

- Synchrotron emission.
- Synchrotron self Compton (SSC)
- External Compton (EC)
- Relativistic Bremsstrahlung and *pp* are negligible.

Clump non-thermal emission

- The most relativistic electrons and protons can diffuse up to the clump.
- Relativistic Bremsstrahlung and *pp* emission.

Clump thermal emission

- The shock in the clump can be radiative.

The case of Cygnus X-3

Binary system: WR + compact object

- $a \sim 3 \times 10^{11}$ cm ($\sim 2\,R_\star$)
- $L_{\rm j} \sim 10^{38}$ erg s^{-1}
- $\dot{M}_* \sim 10^{-5}\,M_\odot$ yr^{-1}
- $L_* \sim 10^{39}$ erg s^{-1}
- $v_{\rm w} \sim 2000$ km s^{-1}

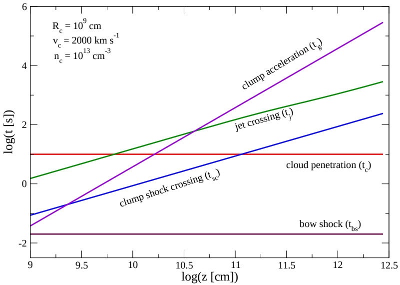
$R_{\rm c} = 10^9$ cm ($\sim 0.01\,R_\star$)

Characteristics of the interaction...

- Interaction height: $z_{\rm int} \gtrsim 2 \times 10^{11}$ cm
- Jet density: $n_{\rm j} \lesssim 5 \times 10^{10}$ cm^{-3}

Interaction timescales

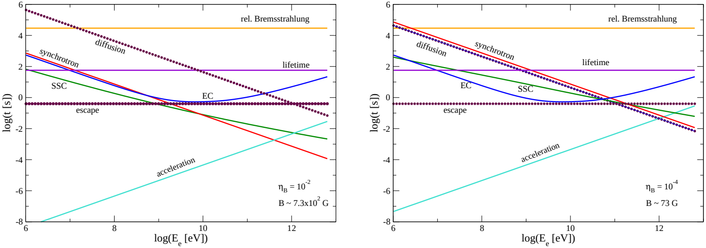
- Clump/jet penetration time: $t_{\rm c} \sim \frac{2\,R_{\rm c}}{v_{\rm c}} \sim 10$ s
- Jet crossing time: $t_{\rm j} \sim \frac{2\,R_{\rm j}}{v_{\rm c}} \sim 70$ s
- Clump shock crossing time: $t_{\rm sc} \sim \frac{2\,R_{\rm c}}{v_{\rm sc}} \sim \frac{2\,R_{\rm c}\sqrt{\chi}}{v_{\rm j}} \sim 600$ s
- Bow-shock formation time: $t_{\rm bs} \sim \frac{3\,R_{\rm c}}{2\,v_{\rm j}} \sim 1$ s



- R-T and K-H instability timescales: $t_{\rm RT,KH} \sim \frac{\sqrt{\chi}R_{\rm c}}{v_{\rm j}} \sim t_{\rm sc}$

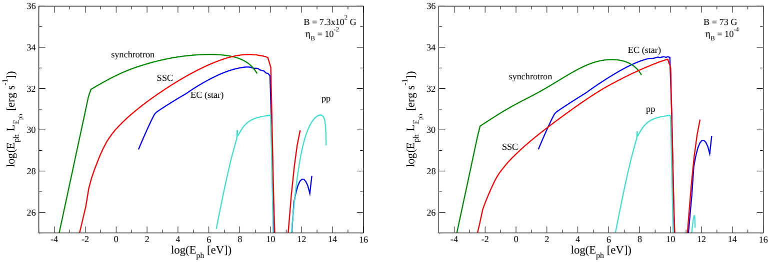
Bow-shock particle acceleration

- Assuming $U_B = \eta_{\rm B} U_{\rm nt} \rightarrow B_{\rm bs} = \sqrt{\eta_{\rm B}}\, 7.3 \times 10^3$ G
- $U_{\rm ph\star} \sim 3 \times 10^4$ erg s^{-1}
- Electrons: $t_{\rm acc} = t_{\rm diff/sinc} \rightarrow E_e^{\rm max} \sim 1$ TeV.
- Protons: $t_{\rm acc} = t_{\rm diff} \rightarrow E_p^{\rm max} \sim 1 - 10$ TeV



Clump + bow-shock emission

- Synchrotron emission is self-absorbed.
- $L_\gamma \gtrsim 10^{34}$ erg s^{-1}.
- $\gamma_\star - \gamma$ absorption: $E_\gamma \gtrsim 10$ GeV.



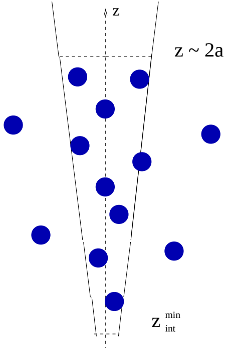
Interaction of many clumps

Filling factor of clumps into the wind: $f \sim 0.01$

Clumps simultaneously in the jet: $N_{\rm c} \sim f\ V_{\rm j}/V_{\rm c}$

If $t_{\rm life} < t_{\rm j/accel} \rightarrow N_{\rm c} < f\ V_{\rm j}/V_{\rm c}$

- $R_{\rm c} = 0.01 R_{\star} \rightarrow N_{\rm c}$ large $\rightarrow$ non flaring activity.
- $R_{\rm c} = 0.1 R_{\star} \rightarrow N_{\rm c}$ small $(< 1) \rightarrow$ flaring activity



Total non-thermal luminosity:

$$L_{\rm nt}^{\rm tot} \sim 2 \int_{z_{\rm min}} \frac{{\rm d}N_{\rm c}^{\rm j}}{{\rm d}z} L_{\rm nt}(z)\, {\rm d}z\,.$$

Conclusions

- The existence of HMMQs and clumps is supported by observations. Then, jet-clump interactions should occur.
- Bow-shock particle acceleration.
- Many small clumps ($R_{\rm c} = 0.01\, R_\star$) inside the jet: large level of emission, flickering in the spectrum.
- Few ($\lesssim 1$) large clumps ($R_{\rm c} = 0.1\, R_\star$) inside the jet: flares
- HE emission is produced via synchrotron, SSC and EC.
- In Cygnus X-3, 1 clump with $R_{\rm c} = 10^9$ cm can produce $L_{\rm ph} \gtrsim 10^{34}$ erg s^{-1} (in the *Fermi* range). But...
- ...$R_{\rm c} = 10^9$ cm $\rightarrow N_{\rm c} \sim 10^4$.