VHE emission in μQ jets/ISM interactions

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ISDC

ICCUB

Outline

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- extragalactic $\longrightarrow$ galactic ?

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- extragalactic $\rightarrow$ galactic ?
- Interaction model

Outline

- extragalactic → galactic ?
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- Hydrodynamical simulations

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- Application to SS433/W50

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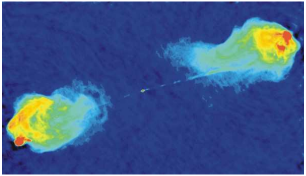
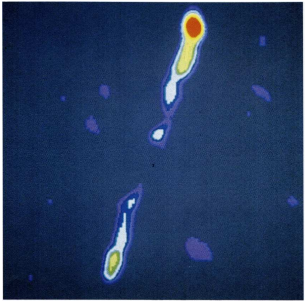
- extragalactic $\rightarrow$ galactic ?
- Interaction model
- Hydrodynamical simulations
- Application to SS433/W50
- Conclusions

Jet-medium interactions

Quasar/IGM interactions $\Longleftrightarrow$ μ-quasar/ISM interactions?



Cygnus A
(Perley et al. 1984)



1E 1740
(Mirabel et al. 1992)

FR galaxies and microquasars

similar jet physics...

- Relativistic jets ($l_{\rm jet} \sim$ light-years in μ-quasars, $l_{\rm jet} \sim$ mega-light-years in quasars)
- Accretion $\longrightarrow$ jet ejection (magnetohydrodynamical?) origin
- Non-thermal radio to γ-ray emission mechanisms
- "Fundamental Plane" $L_{\rm radio} \propto L_{\rm X}^{0.6}\, M_{\rm bh}^{0.8}$ (phenomenological)

...but some (relative) differences

- Heinz (2002): jet-medium interaction dynamics depend on $\eta = \frac{L_{\rm jet}}{R^2}\frac{1}{\rho c_{\rm s}^3}$
- η being $M_{\rm bh}$-independent $\Rightarrow \rho \propto M_{\rm bh}^{-1} \Rightarrow \begin{cases} \rho \gtrsim 10^4 \mathrm{cm}^{-3} & \text{and/or} \\ L_{\rm jet}\ \text{much larger} & \text{and/or} \\ L_{\rm jet}\ \text{more powerful} & \text{and/or} \\ F_\nu\ \text{much fainter} \end{cases}$

- High-mass systems

  SS 433
  Cyg X-1
  Cyg X-3
  LSI 61+303
  LS 5039
  V4641 Sgr

- Low-mass systems

  Cir X-1
  XTE J1550-564
  1E 1740.7-2942
  GRS 1758-258
  H 1743-32
  Scorpius X-1
  GRS 1915+105
  GRO J1655-40
  GX 339-4
  XTE J1748-288

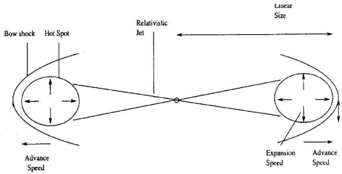
- High-mass systems

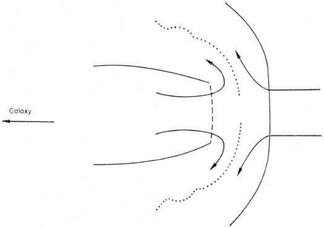
  SS 433 (Zealey et al. 1980, Dubner et al. 1998)
  Cyg X-1 (Martí et al. 1996, Gallo et al. 2005)
  Cyg X-3 ? (Heindl et al. 2003, Sánchez-Sutil 2008)
  LSI 61+303 ? (Paredes et al. 2007, Rea et al. 2010)
  LS 5039
  V4641 Sgr

- Low-mass systems

  Cir X-1 (Tudose et al. 2006, Heinz et al. 2007)
  XTE J1550-564 (Corbel et al. 2002, Kaaret et al. 2003)
  1E 1740.7-2942 (Mirabel et al. 1993)
  GRS 1758-258 (Martí et al. 2002)
  H 1743-32 (Corbel et al. 2005)
  Scorpius X-1 (Fomalont et al. 2001)
  GRS 1915+105 ? (Kaiser et al. 2004, Zdziarski et al. 2005)
  GRO J1655-40
  GX 339-4
  XTE J1748-288

Jet-medium interactions





Extragalactic sources

- Relativistic ($\Gamma \gtrsim 10$), conical + reconfined jets, $l_{jet} \gtrsim 10^{22}$ cm
- Non-thermal "hot spots" and knots (at the reverse shock/recollimation shock?)
- Double radio synchrotron emission lobes
- Stratified environment, $\rho \propto R^{-\alpha}(\alpha \sim 2) \sim 10^{-2} - 10^{-4}$ m_p cm^{-3};

galactic sources

- Mildly relativistic ($\Gamma \sim 1 - 2$) jets, $l_{\rm jet} \gtrsim 10^{19}$ cm
- Jet's $\theta_{\rm init} = 0.1$ rad + reconfinement at $l_{\rm rec} \sim 10^{18}$ cm
- Interaction zones: reconfinement region, cocoon & shell
- $\rho_{\rm ISM} \sim 0.1 - 1.0$ m_p cm^{-3} + companion winds, SNR shell...

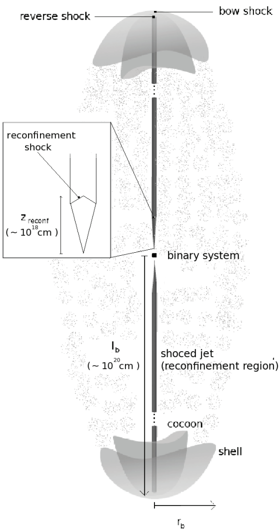
Jet-medium interaction model

Self-similar growing

- Self-similar parameter: $\mathcal{R} \equiv l_{\rm jet} / \, r_{\rm jet}$
- Source basic parameters:
  - Source age $t_{\mu \rm Q} \sim 10^4 - 10^5$ yr
  - Energy injection rate $Q_{\rm jet} \sim 10^{36} - 10^{37}$ erg s^{-1}
  - Medium density $n_{\rm ISM} = 0.1 - 1.0$ cm^{-3}
- Characteristic length: $l_0 = \dfrac{Q_{\rm jet}^2}{\rho_{\rm ISM}^2 c^6 (\Gamma_{\rm jet} - 1)^3]^{1/4}}$

given $l_{\rm jet} \gg l_0$, then

$$\begin{cases} l_{\rm bow} = 1.5 \left(\dfrac{Q_{\rm jet}}{\rho_{\rm ISM}} \right)^{1/5} t_{\rm MQ}^{3/5} \\ v_{\rm bow} = \dfrac{d}{dt}(l_{\rm b}) = \dfrac{3 l_{\rm b}}{5 t_{\rm MQ}} \\ r_{\rm bow} = l_{\rm b} / \mathcal{R} \end{cases}$$



Jet-medium interaction model

shock conditions

- Forward shock: $\mathcal{M} = v_{\rm bow} \cdot (\frac{\rho_{\rm ISM}}{\Gamma_{\rm ISM} P_{\rm ISM}})^{1/2}$, $\rho_{\rm sh} = (\frac{\Gamma_{\rm ISM}+1}{\Gamma_{\rm ISM}-1})\, \rho_{\rm ISM}$, $P_{\rm sh} = \frac{3-(3/5\mathcal{M}^2)}{4} \cdot \rho_{\rm ISM} v_{\rm bow}$
- Reverse shock: $\rho_{\rm shocked} = (\frac{\gamma_{\rm ad}\Gamma_{\rm jet}+1}{\gamma_{\rm ad}-1})\, \rho_{\rm rec.jet}$, $P_{\rm shocked} = (\gamma_{\rm ad} - 1)(\Gamma_{\rm jet} - 1) \cdot \rho_{\rm shocked} c^2$
- Reconfinement shock: $\rho_{\rm shocked} = \frac{\Gamma_{\rm jet}+1}{\Gamma_{\rm jet}-1}\, \rho_{\rm jet}(z)$, $P_{\rm shocked} = P_{\rm cocoon} \sim \frac{Q_{\rm jet}\, t_{\mu Q}}{V_{\rm b}}$; $V_{\rm b} \sim (4/3)\, \pi\, r_{\rm b}^2 \times l_{\rm b}$

non-thermal emitters

- Shell and cocoon: one zone model (B, $U_{\rm ph}$ taken homogeneous); recollimation: $U_{\rm ph}(z)$
- $\int N_0(E)\, E\, dE = \chi\, Q_{\rm jet}$; $N_0(E) \propto E^{-p}$; $p = 2.1$
- $u_{\rm B} = B^2/8\pi = 10\%$ ram/thermal pressure
- Magnetic field equipartition fraction: $B = \eta\, u_e$ in each interaction zone
- $U_{\rm phot} = \begin{cases} \frac{L_\star}{4\ \pi\ c\ l_{\rm bow}^2}; \mathrm{u}_{\rm CMB} & \text{cocoon \& shell} \\ \mathrm{u}(z_{\rm reconf}) \times (\frac{z_{\rm jet}}{z_{\rm reconf}})^2; & \text{reconfinement region} \end{cases}$
- spectral aging of the non-thermal particle populations: $N_0(E) \longrightarrow N(E,t)$

Hydrodyamical simulations

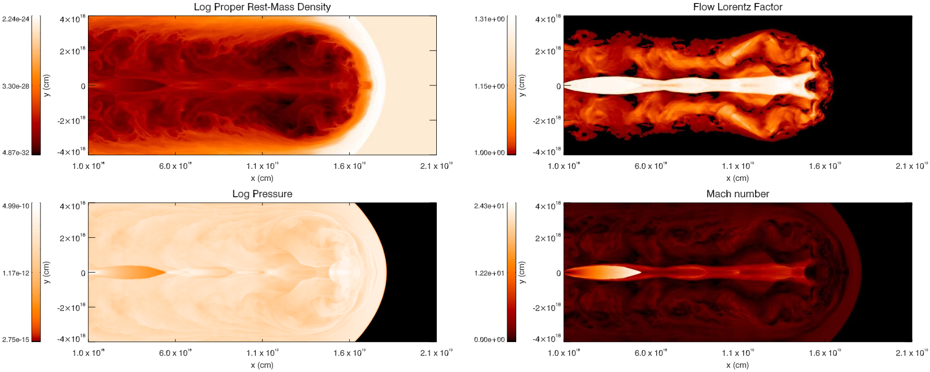
Numerical setup

- two-dimensional finite code to solve the equations of reltivistic hydrodynamics (Perucho et al. 2005, 2007)
- axial symmetry, two-dimensional cylindrical coordinates (R, z)
- low resolution $\longrightarrow$ macroscopic features only (not mixing nor turbulence studies allowed)
- $t_{\rm evol} \approx 5 \times 10^4$ yr

parameter	input value
ambient density	$n_{\rm ext} = \text{cte} = 0.3\ \text{cm}^{-3}$
initial jet density	$n_{\rm jet} = 1.4 \times 10^{-5}\ \text{cm}^{-3}$
jet power	$L_{\rm jet} = 3 \times 10^{36}\ \text{erg s}^{-1}$
source age	$t_{\rm src} = 3 \times 10^4$ yr
initial jet radius	$r_{\rm jet} = 2 \times 10^{16}$ cm
initial jet velocity	$v_{\rm jet} = 0.6\, c$
initial jet Mach number	$\mathcal{M} = 6.5$

Hydrodyamical simulations

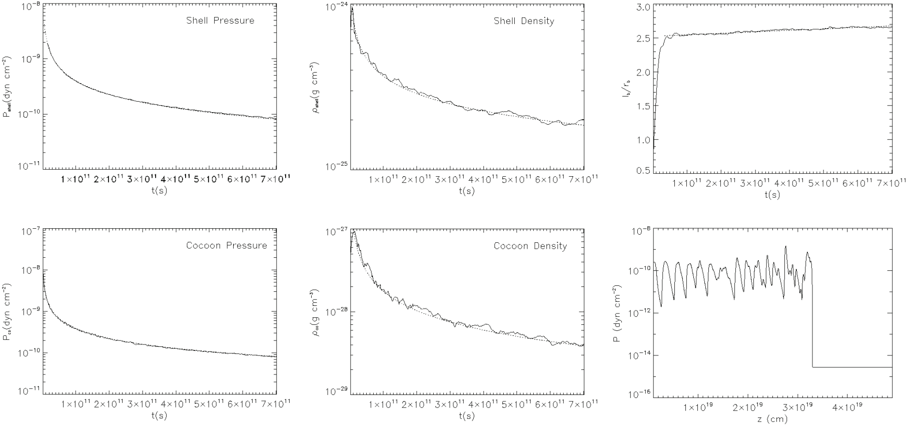
$\rho(z,r)$ and $P(z,r)$ $\Gamma(z,r)$ and $\mathcal{M}(z,r)$



(Bordas et al. 2009)

Hydrodyamical simulations

Pressure and mass densities (shell and cocoon)



hydrodyamical simulations

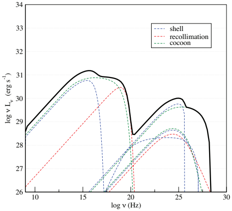
Checking the analytical model

- $l_{\rm bow} \sim 3.3 \times 10^{19}$ cm; $v_{\rm bow} \sim 3 \times 10^{7}$ cm s^{-1}; $\mathcal{R} = 2.7$
- $P_{\rm coc/shell} \sim 10^{-10}$ erg cm$^{-3} \gg P_{\rm ISM}$
- $\rho_{\rm shell} \sim 2 \times 10^{-25}$ g cm^{-3}, $\rho_{\rm coc} \sim 4 \times 10^{-29}$ g cm^{-3}
- strong reconfinement shock at $z_{\rm reconf} \sim 2 \times 10^{18}$ cm

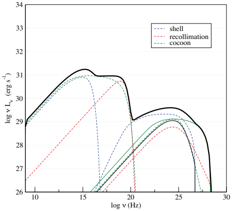
Checking the analytical model

- multiple reconfinement conical shocks after $z_{\rm reconf}$ until $z \lesssim l_{\rm bow}$
- coupling to a Kevin-Helmoltz instability?

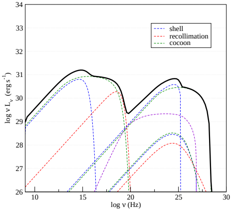
Broadband non-thermal emission



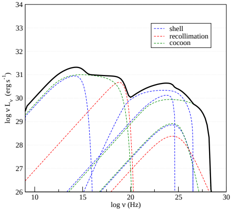
10^4 yr, 10^{36} erg s^{-1}, 0.1 cm^{-3}



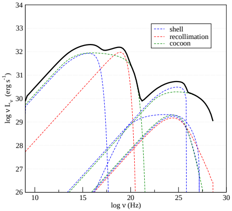
10^4 yr, 10^{36} erg s^{-1}, 1.0 cm^{-3}



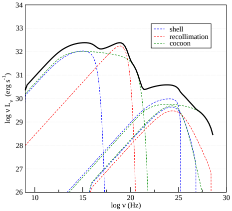
10^5 yr, 10^{36} erg s^{-1}, 0.1 cm^{-3}



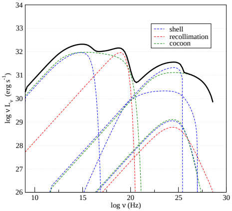
10^5 yr, 10^{36} erg s^{-1}, 1.0 cm^{-3}



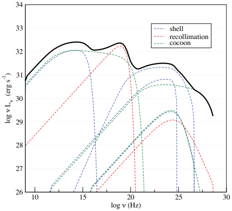
10^4 yr, 10^{37} erg s^{-1}, 0.1 cm^{-3}



10^4 yr, 10^{37} erg s^{-1}, 1.0 cm^{-3}

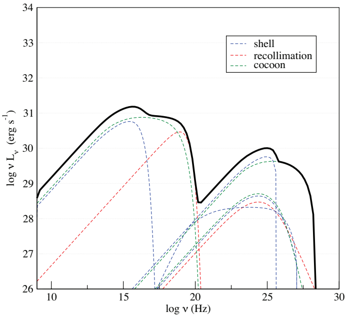


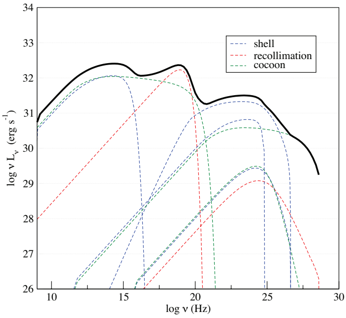
10^5 yr, 10^{37} erg s^{-1}, 0.1 cm^{-3}



10^5 yr, 10^{37} erg s^{-1}, 1.0 cm^{-3}

Broadband non-thermal emission





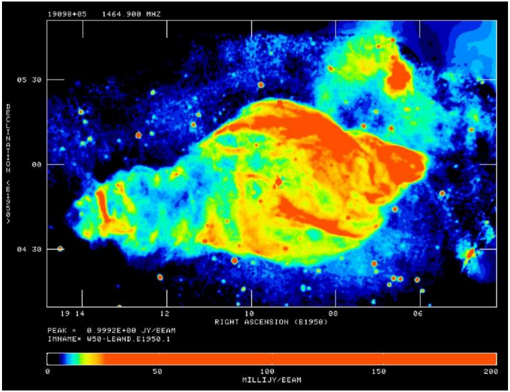
10^{36} erg s^{-1}, 0.1 cm^{-3}, 10^4 yr, $d = 3$ kpc

- $F_{5\,\mathrm{GHz}} \sim 4$ mJy
- $F_{0.1-10\,\mathrm{keV}} \sim 7.3 \times 10^{-15}$ erg cm^{-2} s^{-1}
- $F_{10-100\,\mathrm{keV}} \sim 2.1 \times 10^{-15}$ erg cm^{-2} s^{-1}
- $F_{100\,\mathrm{MeV} \leq \mathrm{E} \leq 100\,\mathrm{GeV}} \sim 1.7 \times 10^{-16}$ erg cm^{-2} s^{-1}
- $F_{>100\,\mathrm{GeV}} \sim 2.8 \times 10^{-17}$ erg cm^{-2} s^{-1}

10^{37} erg s^{-1}, 1.0 cm^{-3}, 10^5 y, $d = 3$ kpc

- $F_{5\,\mathrm{GHz}} \sim 580$ mJy
- $F_{0.1-10\,\mathrm{keV}} \sim 1.4 \times 10^{-13}$ erg cm^{-2} s^{-1}
- $F_{10-100\,\mathrm{keV}} \sim 1.0 \times 10^{-13}$ erg cm^{-2} s^{-1}
- $F_{100\,\mathrm{MeV} \leq \mathrm{E} \leq 100\,\mathrm{GeV}} \sim 2.7 \times 10^{-14}$ erg cm^{-2} s^{-1}
- $F_{>100\,\mathrm{GeV}} \sim 1.5 \times 10^{-15}$ erg cm^{-2} s^{-1}

Application to SS433/W50



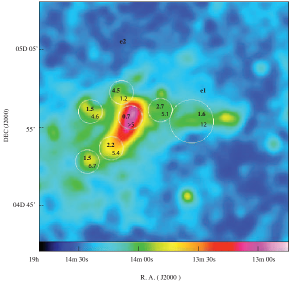
(Dubner et al. 1998)

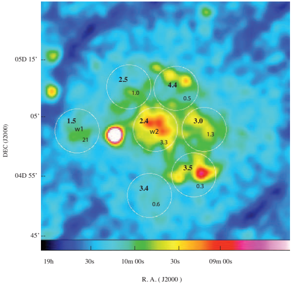
Application to SS433/W50

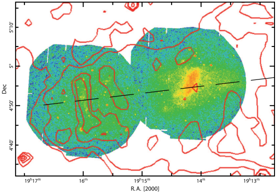
Source description

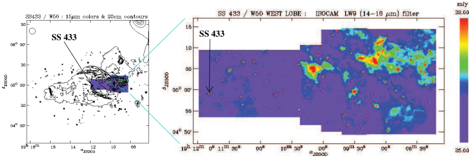
- First stellar compact object where relativistic jets were found (Spencer 1979)
- Binary system: $\sim 9\ \mathrm{M}_\odot$ black-hole and a $\sim 30 \pm 10\ \mathrm{M}_\odot$ A3–7 supergiant companion
- Distance ≈ 5.5 kpc
- P of 13.1 d in a $\sim$ circular orbit, $i \approx 78^\circ$
- Precessing jets ($v_{\rm jet} = 0.26\,c$, $P_{\rm pr} \sim 162$ d, $\theta_{\rm pr} \sim 21^\circ$)
- Doppler shifted iron lines observed up to 10^{17} cm $\Rightarrow$ in-situ reheating?
- Super-Eddington accretion disk, $M_{\rm accr} = 10^{-4}\ \mathrm{M}_\odot/\mathrm{y}$
- Interaction with the surrounding W50 nebula ($\Rightarrow L_{\rm jet,kin} \sim 10^{39}$ erg s^{-1})
- Non-thermal radio-to-X-ray hot-spot emission both in the East and West "ears"

Non-thermal emission from east and west interaction regions









Observations of SS433 at VHE gamma-rays

Previous observations

- HEGRA observations in 1998–2001, for $t_{obs} \geq 100$ h (Aharonian et al. 2005)

Source	Obs. time [h]	$^{a}E_{\rm th}$ [TeV]	$\theta_{\rm cut}$ [deg]	s	b	^{b}S	$^{c}\phi^{99\%}_{\rm crab}$ [σ]	$^{d}\phi^{99\%}$
— SS-433/W50 and associated —								
SS-433 *e1*	72.0	0.8	0.13	315	1972	−0.4	**0.023**	**6.18**
SS-433 *e2*	73.1	0.8	0.21	794	4980	−0.7	**0.034**	**9.18**
SS-433 *e3*	68.8	0.8	0.28	1247	8108	−2.0	**0.032**	**8.96**
SS-433	96.3	0.8	0.15	433	2541	+0.8	**0.032**	**8.93**
SS-433 *w1*	104.9	0.7	0.14	352	2168	−0.1	**0.024**	**6.65**
SS-433 *w2*	100.7	0.7	0.14	334	1994	+0.4	**0.031**	**9.00**

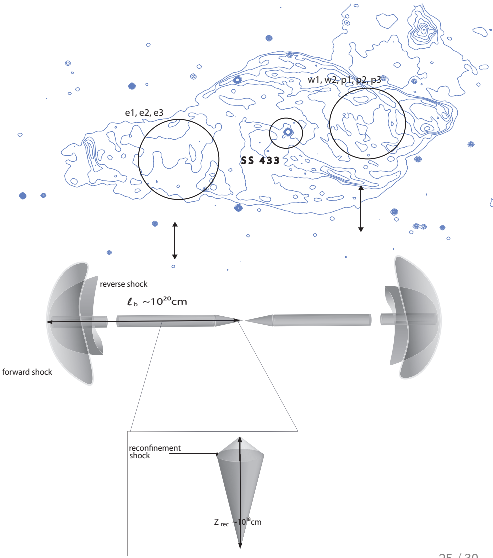
- CANGAROO-II observations in 2001–2002 of the western interaction region for $t_{obs} \sim 85$ h (Hayashi et al. 2009, `astro-ph 0909.0133`)

Source	R.A.	Decl.	$^{a}N_s$	^{b}S	$^{c}\phi^{99\%}$
p1	$19^{\rm h}10^{\rm m}17^{\rm s}$	$+4°57'46''$	39	0.39	1.5
p2	$19^{\rm h}09^{\rm m}44^{\rm s}$	$+4°58'48''$	-12	-0.11	1.3
p3	$19^{\rm h}09^{\rm m}12^{\rm s}$	$+4°59'13''$	-97	-1.0	0.79

Jet-medium interaction model

Interaction model applied

Parameter	*Value*
Jet kinetic power $Q_{\rm jet}$ (erg s $^{-1}$)	10^{39}
ISM density $n_{\rm ISM}$ (cm^{-3})	1
Source age $t_{\rm MQ}$ (yr)	5×10^4
Jet Lorentz factor $\Gamma_{\rm jet}$	1.04
Jet opening angle Ψ ($^\circ$)	1.2
Star Luminosity $L_\star$ (erg s $^{-1}$)	10^{39}
Self-Similar parameter $\mathcal{R}$	3
Non-thermal fraction χ	0.01



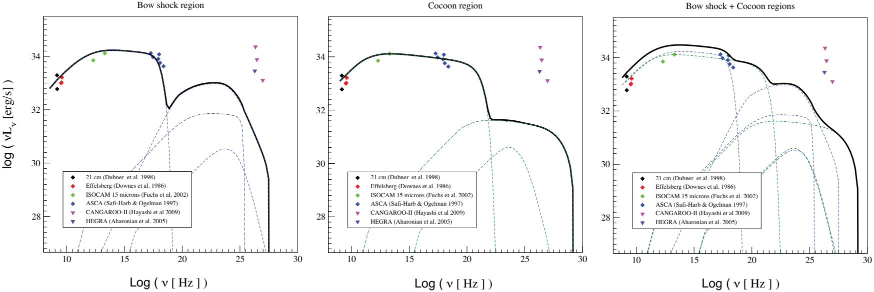
SS433/W50 interaction

- Bow shock at $\sim 6 \times 10^{20}$ cm
- Reverse shock at $\sim 4.5 \times 10^{20}$ cm
- Cocoon's width $\sim 5 \times 10^{19}$ cm

Physical properties	Inferred values
SHELL	
Magnetic field B (G)	6×10^{-5}
Shock velocity v_{b} (cm s^{-1})	4.4×10^{7}
Emitter size r (cm)	2.3×10^{20}
Rad. energy dens. $u_{\star}$ (erg cm^{-3})	5.0×10^{-14}
Maximum energy E_{max} (TeV)	54.2
Target density n_{t} (cm^{-3})	4.0

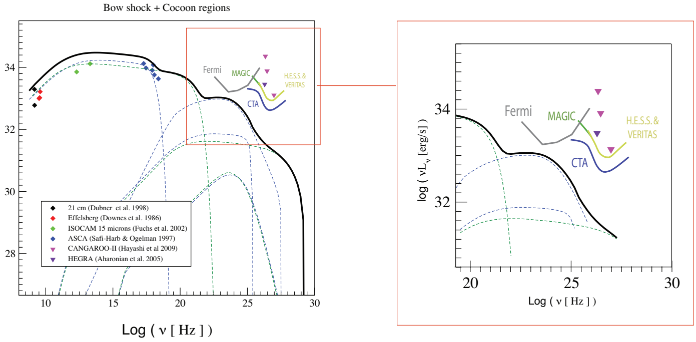
Physical properties	Inferred values
COCOON	
Magnetic field B (G)	3.8×10^{-5}
Shock velocity v_{S} (cm s^{-1})	1.6×10^{10}
Emitter size r (cm)	5.5×10^{19}
Rad. energy dens. $u_{\star}$ (erg cm^{-3})	6.4×10^{-14}
Maximum energy E_{max} (TeV)	280.5
RECONFINEMENT	
Magnetic field B (G)	5.2×10^{-5}
Shock velocity v_{conf} (cm s^{-1})	1.9×10^{9}
Emitter size r (cm)	1.9×10^{17}
Rad. energy dens. $u_{\star}$ (erg cm^{-3})	2.5×10^{-10}
Maximum energy E_{max} (TeV)	5.2

SS433/W50 interaction



- Radio: 1465 MHz eastern wing flux $\sim$ 15 Jy $\longrightarrow$ (Downes et al. 1981; Dubner et al. 1998) $\Rightarrow \sim 10^{33}$ erg s^{-1} ($d = 5.5$ kpc) $\approx$ predicted by the model.
- X-rays: $L_{0.4-4.5\ \mathrm{keV}} \sim 10^{34}$ erg s^{-1} (Safi-Harb & Petre 1999) $\sim$ X-ray flux from both the bow shock and cocoon (although it extends to higher energies in this case)

SS433/W50 interaction



- γ-rays: $E \geq 100$ GeV $= 2.27 \times 10^{-14}$ ph cm^{-2} s^{-1} $\ll$ current Cherenkov sensitivities $<$ next CTA sensitivities ?

Conclusions

- Extragalactic interaction model easily applied to μ-quasars
- hydrodynamical simulations $\longrightarrow$ pressures, mass densities and source geometry: good agreement with analytical model
- Multiple conical shocks present in hydrodynamical simulations, *vs* one only shock in the analytical model
- Radio to X-ray fluxes could be detected, gamma-ray fluxes too faint (see however Zhang & Feng 2010)
- Dependence on the ambient density profile not accounted for
- *pp* interactions not studied (e.g., Heinz & Sunyaev 2002)
- SS 433/W50: strong candidate (high $L_{\rm jet}$, high $n_{\rm ISM}$ in the W50 nebula)
- interactions remain undetected at VHE γ-rays (HEGRA & CANGAROO-II): target for next generation IACTs?)

Zhang & Feng (2010):
"Non-thermal emission from the termination of microquasar jets"

Application to Cyg X-1

Table 2. Parameters adopted to calculate SEDs.

Paramete1	Fig. 2	Fig. 3	Fig. 4
Ratio of L_{jet} to L_{non}	0.01	0.1	0.1
Source age t_4 (10^4 yr)	3	3	3
L_{39} (10^{39} erg s^{-1})[a]	1	1	1
Power-law index	1.8	2	1.8
Temperature T_4 (10^4 K)[b]	3	3	3
Diffusion radius R(pc)	3.5	3	3
Magnetic field B (μG)	12	6	5.5
Ratio of L_e to L_p (K_{ep})	0.01	1	1
Shell width r_{sh} (pc)	0.8	0.6	0.7
Shell density n_H (cm^{-3})	250	1000	900
Shell length l_{sh} (pc)	10	9	11

[a]Indicates the luminosity of stellar companion.
[b]The stellar effective surface temperature.

Figure 2.

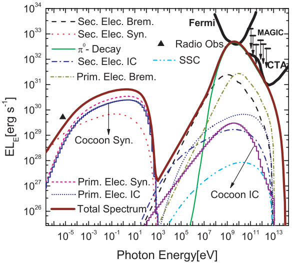


Figure 3.

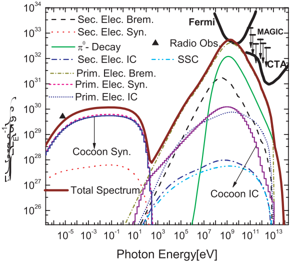


Figure 4.