Black hole microquasars: gamma ray and neutrino emission

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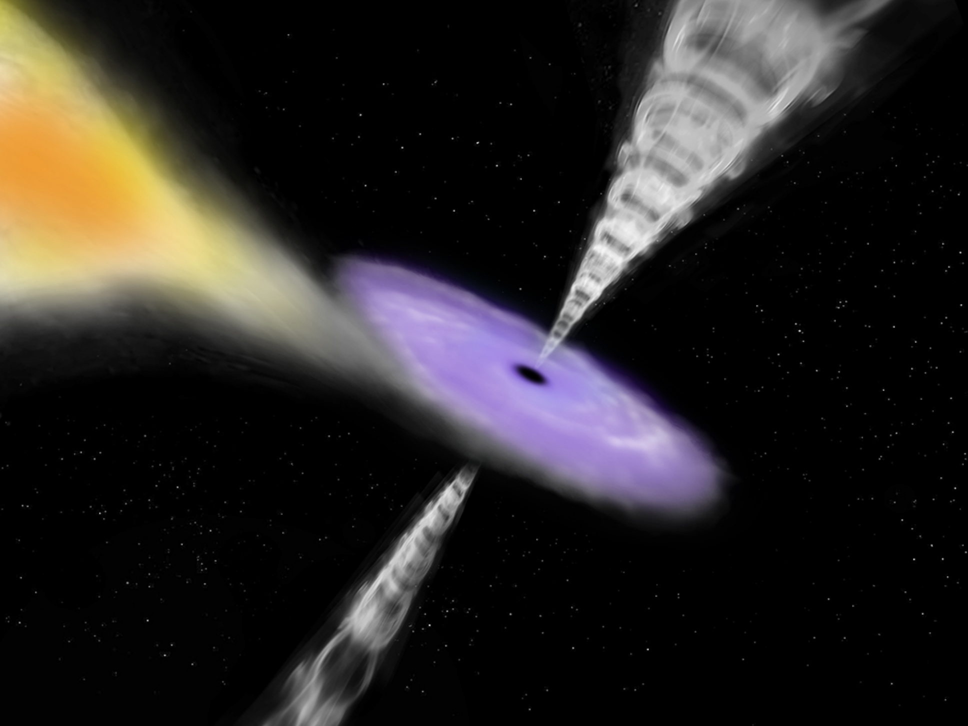
3rd Workshop on New Aspects and Perspectives in Nuclear Physics
April 8, Athens 2016

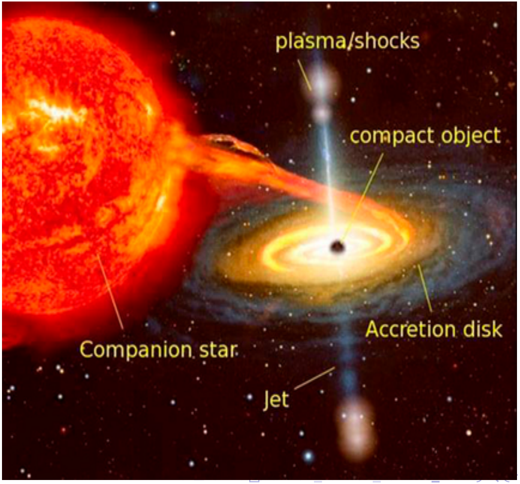


Overview

Definition

Microquasars are X-Ray Binary Stars with twin collimated relativistic jets[1]

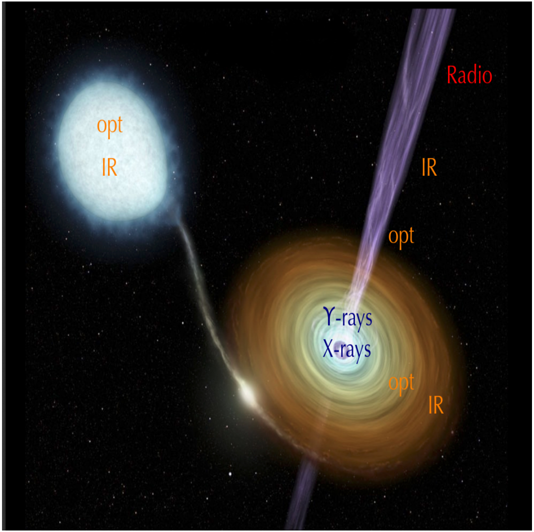
- **Companion (donor) star**
  A main sequence star in coupled orbit with the compact object
- **Accretion disk**
  consists of plasma flowing from donor star to the compact object
- **Jet**
  plasma outflows, perpendicular to the disk
- **Compact object**
  Black Hole or Neutron Star



[1] F. Mirabel *et. al.*, 1999

An Observational view

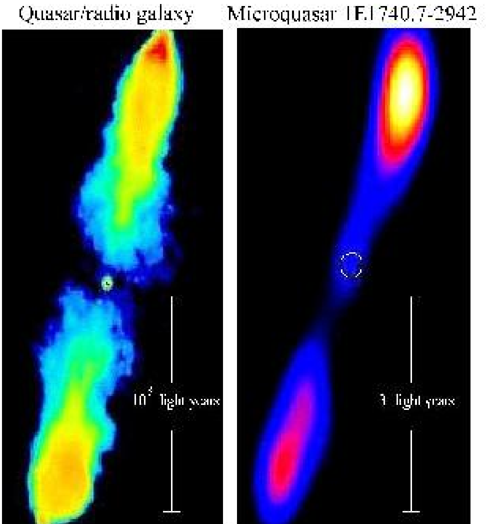
- **Jet**→ Radio, IR and opt. wavelengths
- **Donor star**→ optical and IR wavelengths
- **Accretion disk**→ γ-rays and X-rays (center), optical and IR wavelengths (away from the compact object)



Why?

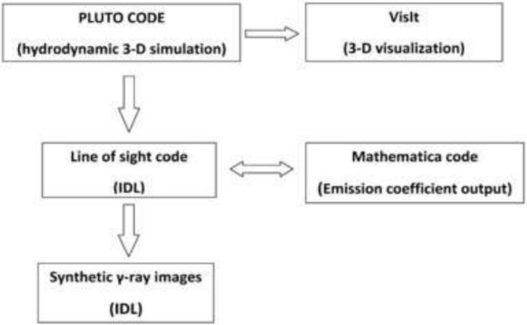
Analogy with AGN

- **Time scales**→ proportional to the black hole mass
- **Similar phenomenology**
- **Cosmological importance**



Simulation of the neutrino & gamma ray emission from MQs

Outline of our work[2]



[2] T. Smponias, T. S. Kosmas, MNRAS, 2011

Neutrino producing reactions

Main contribution to neutrino emissivity in MQs jets, is due to pp collisions[3]

- $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ *prompt* neutrinos
- $\mu^{\pm} \rightarrow e^{\pm} + \nu_{\mu} + \nu_{e}$ *delayed* neutrinos

Remarks:

- The jet is considered to be of hadronic substance
- The proton-proton collision with energy threshold of: $E_{thres} = 1.22 GeV$
- Only a tiny portion of the bulk flow protons accelerated from the 1st order Fermi acceleration[4] to energies up to 10^7GeV

[3] M. M. Reynoso & G. E. Romero, Astron.& Astrophys., 2013

[4] F. M. Rieger *et al*, Astrophys. Space Sci., 2007

Assumptions

- We speculate that we have hadronic jets consisting of protons only.
- The source from which the secondary particles (pions) are injected is isotropic and time-independent.
- One-zone approximation:The particle acceleration happens in such a way that the diffusion effects could be ignored.
- Only the synchrotron and adiabatic expansion energy loss mechanisms are considered.
- The primary particles (protons) are accelerated via 1st-order Fermi mechanism only.
- Only prompt neutrinos are considered.

Mechanisms of Energy Loss/Gain

- The acceleration to energy E_p rate via 1st-order Fermi mechanism[5] $t^{-1}_{accel.} \simeq \frac{ceB}{E)p}$
- The particle can escape from the volume cell, $t^{-1}_{esc}(z) \cong \frac{c}{z}$
- The jet expands adiabatically, $t^{-1}_{ad} = \frac{2u_b}{3z}$
- A charged particle moving with relativistic velocity into a magnetic field emits synchrotron radiation, $t^{-1}_{sync} = \frac{4}{3}\left(\frac{m_e}{m_p}\right)^3 \frac{\sigma_T B^2 \gamma_p}{m_e c}$
- There are also energy losses due to photopion production, $t^{-1}_{p\gamma}(E)$

[5] Begelman et al.,ApJ, 1990

$\pi^{\pm}$ injection function

The injection function of pions produced by pp interactions is given by[6]:

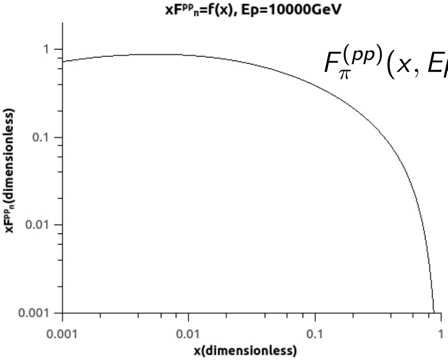
$$Q^{(pp)}_{pion}(E) = nc \int_{\frac{E}{E_{max}}}^{1} \frac{dx}{x} N_p\left(\frac{E}{x}\right) F^{(pp)}_{\pi}\left(x, \frac{E}{x}\right) \sigma^{inel}\left(\frac{E}{x}\right)$$

where E stands for pion energy and $x = E/E_p$,with E_p the proton energy

- $\sigma^{inel}(E_p) = (34.3 + 1.88L + 0.25L^2)\left(1 - \left(\frac{E_{p,thr.}}{E_p}\right)^4\right)^2$: cross section for inelastic pp collisions
- $F^{(pp)}_{\pi}$: distribution function of pions per pp collisions
- $N_p = \frac{K_0}{E_p^{\lambda}}$: injection rate of fast protons, $\lambda = 2$

[6] M. M. Reynoso & G. E. Romero, A& A, 2013,

Pion Distribution



$$F_{\pi}^{(pp)}(x, Ep) = 4\alpha B_{\pi} x^{\alpha-1}\left(\frac{1-x^{\alpha}}{1+rx^{\alpha}(1-x^{\alpha})}\right)^{4} \times\left(\frac{1}{1-x^{\alpha}}+\frac{r(1-2x^{\alpha})}{1+rx^{\alpha}(1-x^{\alpha})}\right) \times\left(1-\frac{m_{\pi}c^{2}}{xE_{p}}\right)^{1/2}$$

Functions and Parameters

The fitting parameters[7] B_π, r, a, L, α written for our convenience:

- $$L = ln\frac{E_p}{1000GeV}$$
  $$a = 3.67 + 0.83L + 0.075L^2$$
  $$r = 2.6/a^{0.5}$$
  $$B_\pi = a + 0.25$$
  $$\alpha = 0.98/a^{0.5}$$
- n : density of cold particles at the volume of concern

[7] Kelner *et al.*, PRD, 2006

Parameters of the fast protons injection

$$K_0 = \frac{4 q_{rel} L_k}{c R_0^2 \ln\left(\frac{E_p'^{max}}{E_p'^{min}}\right)}$$

- q_{rel}: fraction of the total bulk energy carried by non-thermal protons. From HEGRA limits we adopt $q_{rel}^{max} \cong 2.9 \times 10^{-4}$
- L_k: kinetic luminosity of the jet (energy flow from a surface co-moving with the jet) $L_k \sim 10^{39}$erg/sec
- R_0: initial radius of the jet cros-section i.e $R_0 \simeq 5 R_{Sch}$

Radio image of supernova remnant W50 in green, with infrared background in red, NRAO/AUI/NSF

Parameters for PLUTO's jet simulation

Parameter		Comments
cell size ($\times 10^{10}$cm)	0.25	PLUTO's computational cell
ρ_{jet} (cm^{-3})	1.0×10^{11}	initial jet matter density
ρ_{sw} (cm^{-3})	1.0×10^{12}	stellar wind density
ρ_{adw} (cm^{-3})	1.0×10^{12}	accretion disk wind density
t_{run}^{max} (s)	1.5×10^{3}	model execution time
Interpolation Method	Linear	
Integrator	MUSCL-Hancock	
EOS	Ideal	Equation of state
BinSep (cm)	4.0×10^{12}	Binary star separation
M_{BH}/M_{sun}	3-10	Mass range of collapsed star
M_{star}/M_{sun}	10-30	Mass range of Main Seq. star
$\beta = v_0/c$	0.26	Initial jet speed
L_k^p	2×10^{36}	Jet kinetic luminocity
grid resolution	$120 \times 200 \times 120$	PLUTO grid resolution (xyz)

Parameters for the calculation in a PLUTO's cell

Parameters	Values	Comments
z(cm)	10^{11}	Cell's characteristic dimension
$M_{BH}(M_{solar})$	10	Compact Object Mass
$n(1/cm)^3$	10^{10}	Cold protons numerical density
E_p^{max} (GeV)	10^7	Maximum energy of a fast proton
E_p^{min} (GeV)	1.22	Threshold energy for p-p interaction
E_n^{max} (GeV)	10^7	Maximum energy of a pion produced from a fast proton
E_n^{min} (MeV)	139.5	Pion energy at rest
B(G)	400	Characteristic value of the magnetic field in the jet

Steady state Pion Distribution

The time-independent pion distribution is derived from the transport equation $\frac{\partial N(E,z)}{\partial E} b(E,Z) + t_{\pi}^{-1}(z)N(E,z) = Q(E,z)$

$$N_{\pi}(E,z) = \frac{1}{\mid b_{\pi}(E) \mid} \int_{E}^{E^{max}} dE' Q(E',z) e^{-\tau_{\pi}(E,E')}$$

with

$$\tau_{\pi}(E',E) = \int_{E'}^{E} \frac{dE'' t_{\pi}^{-1}(E'',z)}{\mid b_{\pi}(E'') \mid}$$

- $b_{\pi}(E) = -E(t_{syn}^{-1} + t_{ad}^{-1} + t_{\pi p}^{-1} + t_{\pi\gamma}^{-1})$ where t^{-1}
- $t_{\pi}^{-1}(E,z) = t_{esc}^{-1}(z) + t_{dec}^{-1}(E)$:is the total rate of a pion extinction from the unit volume (sum of pion decay rate and escape rate)

Neutrino emission

The total emissivity of neutrinos is[8]

$$Q_\nu(E,z) = Q_{\pi\to\nu}(E,z) + Q_{\mu\to\nu}(E,z)$$

where:

$$Q_{\pi\to\nu}(E,z) = \int_E^{E_{max}} dE_\pi t^{-1}_{\pi,dec}(E) N_\pi(E_\pi,z) \times \frac{\Theta(1-r_\pi-x)}{E_\pi(1-r_\pi)}$$

E:now is neutrino energy!
and $r_\pi = \left(\frac{m_\mu}{m_\pi}\right)^2$

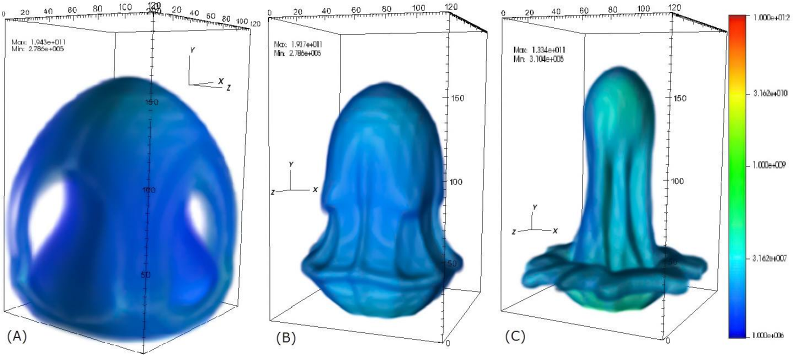
- We neglect the contribution of $\mu^\pm$ decay[9]
- The z dependence is not present, as we calculate the aforementioned quantities into a PLUTO cell

[8] Lipari *et al.*, PRD, 2007

[9] T. Smponias, O. T. Kosmas, Advan. High Energy Phys., 2015

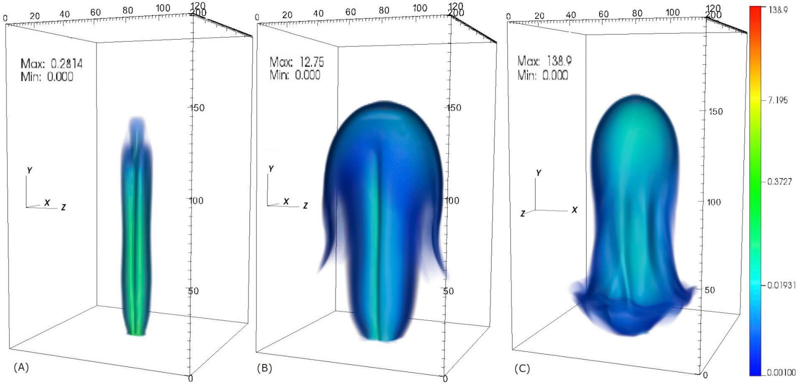
Mass Density for some MF values at the base of the jet

- 2 G
- 50 G
- 500 G

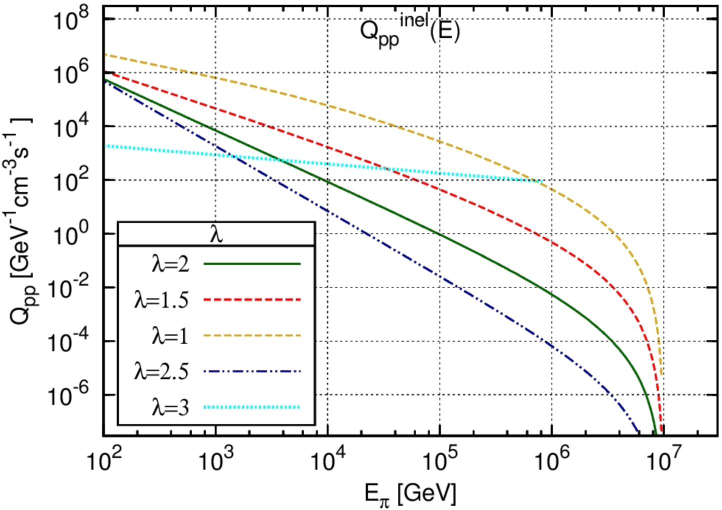


MF Magnitude for some MF values at the base of the jet

- 2 G
- 50 G
- 500 G

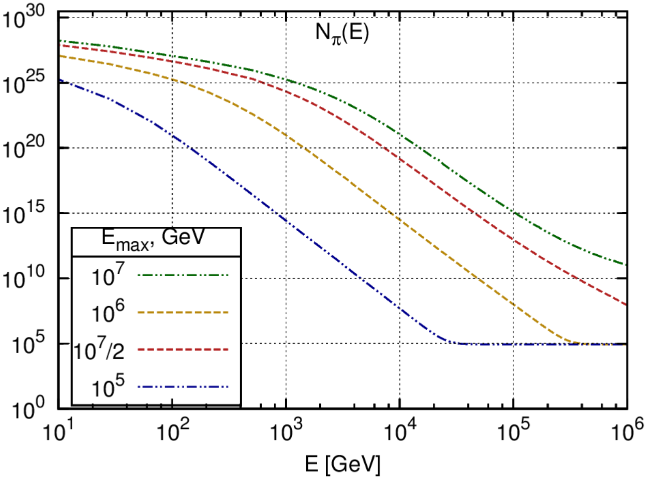


Pion Injection Function



Steady State Pion Distribution

for $L_k = 10^{39} erg/s$ and $q_{rel} = 2.9 \times 10^{-4}$



Conclusions

- The neutrino emission modeling is a useful tool for exploring the physical conditions in MQ jets (i.e shock waves propagation)
- The employed methods can also be used for the gamma rays emission of the jets.
- There is a strong dependence of the jets collimation and neutrino emission on the magnetic field.
- The numerical tool that created could be used in future work to obtain more realistic results.

Future work

- Efficient calculation of neutrino emissivity (in progress)
- Extension of the adopted model to include more neutrino producing reactions
- Consideration of extra leptonic content in the jet

Our team

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THE END
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