High Energy Neutrino Emission from Black-Hole Micro-Quasars

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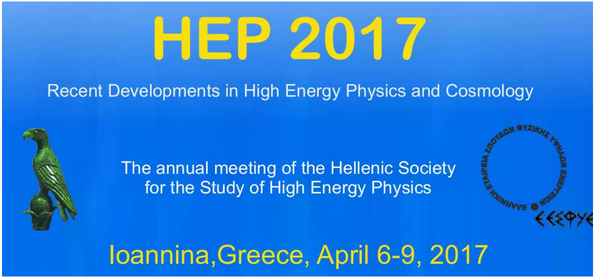
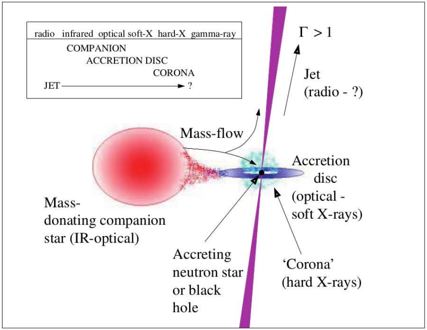


Overview of the Talk

- Introduction
  - A typical X-ray binary system
  - p-p collisions in hadronic jets of MQs
- High Energy γ-ray and ν-emission from MQ Jets
  - Semi-analytical Approach
  - Explicit solution of Transport Equation
- Dynamical Simulations with PLUTO RMHD-code
- Summary and Conclusions

A typical X-ray binary (Micro-quasar) system

The most common cases of X-ray binary stars comprise a compact star (usually a black hole or a neutron star), and the donor star, a normal star still evolving.
The spectral extent of such a system can be very broad. The classical BH candidate (BHC) XRB, Cyg X-1, is a well-detected source from the radio band to high energy γ-rays and neutrino emission.



A generally accepted structure of a typical X-ray binary system.

Mechanisms of mass Loss of a Star

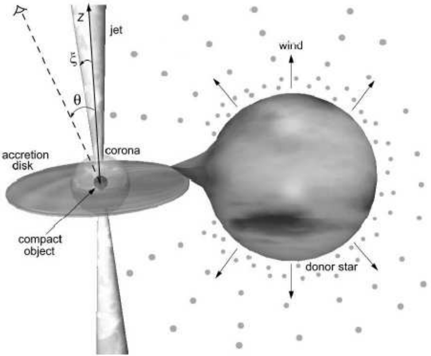
During their evolution one of the stars may lose mass through four basic mechanisms:

- One of the stars may eject mass in the form of a stellar wind
- Eruptive or equatorial loss from rapidly spinning (of the compact object)
- X-ray emission of the compact object can irradiate the outer layers of the companion star causing or increasing the mass transfer rate
- Over the course of their stellar evolution, one of the two stars in a binary system may increase its radius or the binary separation may shrink to the point where the gravitational pull of the compact object gradually removes the outer layers of its envelope

Geometry of a High Mass (BH) Microquasar

Jet Parameters

- $\xi \approx 1 - 1.5^o$: Jet's half-opening angle
- $\theta \approx 30^o$:Viewing angle



- Due to the rotation of the binary system, gas flowing through point-L_1 will have relatively high angular momentum. Too large to directly accrete onto the compact object

M. Reynoso and G. Romero, A&A 493, 1-11 (2009)

Hadronic Jets of MQ: p-p Collisions

- Plasma is ejected from the accretion's disc center, due to magneto-centrifugal force (direction perpendicular to disc).
- In the interior of the jet, bulk flow particles (protons) are mostly thermal (move 'slowly', following the jet stream). Through first order Fermi process, a small portion of protons are accelerated (non-thermal protons). p-p collisions of non-thermal protons on thermal ones create secondary particles (charged $\pi^{\pm}$, $K^{\pm}$, $\mu^{\pm}$ etc.).

  The pions produce neutrinos according to the reactions:

$$\begin{array}{ll} \pi^+ \to \mu^+ + \nu_\mu, & \pi^+ \to e^+ + \nu_e \\ \pi^- \to \mu^- + \bar{\nu}_\mu, & \pi^- \to e^- + \bar{\nu}_e \end{array}$$

$$\begin{array}{l} \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu \end{array}$$

Left boxes: prompt neutrinos. Right box: Delayed neutrinos. It is not possible to distinguish those experimentally (terrestrial experiments, FermiLab, J-PARC, etc. may separate them).

Description of Neutrino Produced from MQ jets

- The description of the energy spectrum and composition of the primary particles.
- The definition of the target material with which the primary particles interact
- The modelling of the properties of particle production in hadronic interactions (energy distributions).
- The description of the properties of the medium where the interactions occur, to determine the relevant mechanisms for energy loss.
- The (well-known) properties of weak decays

Because of the limited statistics and angular resolution, the observations of astrophysical neutrinos will necessarily integrate over the entire volume of the source (in most cases they appear as point-like) and average over time variations. Describing this situation, requires the averaging over different source regions and conditions

The Scheme followed by the Calculations

- First, the rate of production of the secondary particle of type α, $Q_\alpha(E_\alpha)$, can be calculated though the convolution procedure
- The energy distribution of the particle α at decay, in general, differs from the distribution at production
- The neutrinos created in the direct decay of particle α are calculated
- The muon production rate can be calculated with an analogous expression (by substituting the appropriate decay distributions)
- Finally we sum over weakly decaying particles ($\pi^\pm, K^\pm$, etc. (neglecting much smaller contributions coming from heavier particles)
- The last step is to compute the neutrinos generated by muon decay delayed neutrinos
- The neutrino flux is obtained by summing over all possible sources

Neutrino Production

For example, it holds that (*Lipari et al*, 2007):

$$\frac{dn_{p\to\pi}(E;E_p)}{dE} = \frac{1}{E_p}F_\pi^{(pp)}\left(\frac{E}{E_p}\right)$$

where $F_\pi^{(pp)}$ denotes the energy density of the produced pions as a function of ratio $x = E/E_p$, with $E = E_\pi$.
Neutrinos produced (directly from the decay of a particle α are described by the relation

$$Q_{\alpha\to\nu_\alpha}(E_\nu) = \int_{E_\nu}^{\infty} Q_\alpha^{dec.}(E_\alpha)\frac{dn_{\alpha\to\nu_\alpha}(E_\nu;E_\alpha)}{dE_\nu}dE_\alpha$$

The energy distribution of muons before their decay is given by

$$Q_{\mu_h^\pm}^{dec.}(E) = \int_{E}^{\infty} Q_{\mu_h^\pm}(E_i)\frac{dP_{dec}^{\mu}(E;E_i)}{dE}dE_i$$

Phenomenological descrition

By using simulation codes (*SIBIL, QGSJET*, QCD purturbation theory codes), and then fitting, (*Kelner, et al.*) , 2006) obtained semi-analytical expressions, for the interaction cross section and the pion energy-distribution (per *pp*-collision), etc.

$$Q_\pi^{pp}(E) = n_{gas} c \int_{\frac{E}{E^{(max)}}}^{1} N_p\left(\frac{E}{x}\right) F_\pi^{(pp)} \sigma_{pp}^{inel}\left(\frac{E}{x}\right) \frac{dx}{x}$$

where $x = \frac{E}{E_p}$ with $dE_{(p)} = -\frac{1}{x^2} E dx$.

Neutrino production from muon decay

- The neutrinos obtained from muon-decay are

$$Q_{\mu_h^\pm \to \nu_\alpha}(E_\nu) = \int_{E_\nu}^{\infty} Q_{\mu_h^\pm}^{dec.}(E_\mu) \frac{dn_{\mu_h^\pm \to \nu_\alpha}(E_\nu; E_\mu)}{dE_\nu} dE_\mu$$

- The energy distribution of muons before decaying may be written as

$$Q_{\mu_h^\pm}^{dec.}(E) = \int_{E}^{\infty} Q_{\mu_h^\pm}(E_i) \frac{dP_{dec}^{\mu}(E; E_i)}{dE} dE_i$$

Total Neutrino emissivity

- The total neutrino emissivity is calculated by adding up contributions coming from the decay of secondary particles (pions, kaons etc.) and from muon decay.

$$Q_{emiss}(E_\nu) = \sum_{\alpha\to\nu}^{\alpha} Q_{\alpha\to\nu_\alpha}(E_\nu)$$

Transport Equation

We start from a pion distribution $N_\pi(E_p)$ which satisfies the equation:

$$\frac{\partial N_\pi}{\partial t} - \nabla(D_\pi \nabla N_\pi) + \frac{\partial(b_\pi N_\pi)}{\partial E} + \frac{N_\pi}{T} = Q(E, \mathbf{r}, t)$$

- $\nabla(D_\pi \nabla N_\pi)$: Describes the spatial diffusion of pions.
- $\frac{\partial(b_\pi N_\pi)}{\partial E}$: Describes the energy variation of N_π due to acceleration and collision of protons.
- $b_\pi(E, z) = -E \cdot (t_{sync}^{-1} + t_{adb}^{-1} + t_{\pi p}^{-1})$
- $Q(E, \mathbf{r}, t)$: Intensity of the $\pi^\pm$ source.
- $\frac{N_\pi}{T}$: Catastrophic collision or exit of the energy band.

By solving numerically this equation, we compute the pion distribution $N_\pi(E_p)$ which produces the neutrino beam of our interest.

Explicit Solution of the Transport ODE

By neglecting the spatial diffusion and time dependence inside the jet, the transport equation takes the simple form:

$$\frac{\partial(b_\pi N_\pi)}{\partial E} + \frac{N_\pi}{T} = Q(E, \mathbf{r})$$

Neutrino emissivity is subsequently obtained through the (numerical) integration:

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

where:

- $t^{-1}_{\pi,dec} = (2.6 \cdot 10^{-8} \cdot \gamma_\pi)^{-1} (s^{-1})$, $\quad r_\pi = (\frac{m_\mu}{m_\pi})^2$, $\quad x = \frac{E_\mu}{E_p}$

M. Reynoso and G. Romero, A&A 493, 1-11 (2009)

Dynamical simulations in MQs. Jet density evolution

- Modern Relativistic Magneto-Hydro-Dynamical (RMHD) hydrocode used for the dynamic calculation (PLUTO).
- High Energy γ-ray and ν-emission calculated from the model jet.
- When model-results match observations, initial conditions of model are then considered to approximate the actual ones at the source.
- Initial results already compared to actual observations and detector output.

Important model parameters

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 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)

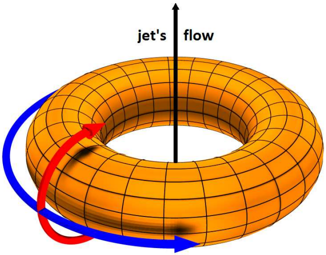
These parameter values (in c.g.s.) are fitted to SS 433 MQ data.

Smponias, Kosmas, Advances in High Energy Physics 921757, (2015)

Role of magnetic fields in the propagation of MQ jets

- We simulate **"RMHD"** jet's flow, for different magnetic fields values and derive 2-D and 3-D visualisations.
- We may investigate the moderation of the MF on the emission of high energy neutrinos and γ-rays, produced from the collisions.

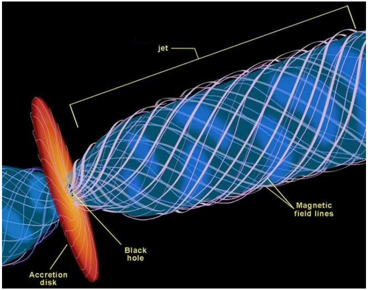
MF components:



- Toroidal component, (B_ϕ)
- Poloidal component, (B_p) (opposite conversion than fusion)

Jet formation/confinement

- Accretion disk rotation (alternatively, GR frame dragging) causes rotation of the matter.
- The acceleration of the jet is supported by an accretion disk threaded by a perpendicular magnetic field.
- The magnetic field lines are stretched by the material (fixed on the lines) ending up surrounding them.
- At relativistic jets, the direction of the outgoing flux injection is determined by the angular momentum axis of the accretion disk (also by the spin of the central object).



Processes Inside the Relativistic Jet

Before decaying, $\pi^{\pm}$ and $\mu^{\pm}$ may interact, losing energy through various processes:

- Synchrotron Radiation: Charged particles of mass m and energy $E = \gamma mc^2$ emit synchrotron radiation at a rate:

$$t_{sync}^{-1} = \frac{4}{3}\left(\frac{m_e}{m}\right)^3 \frac{\sigma_T B^2 \gamma}{8\pi m_e c}$$

- Proton-Pion Collisions: A portion of the pions collide with thermal protons at a rate:

$$t_{\pi p}^{-1}(E, z) \approx \frac{n(z) c \sigma_{\pi p}^{(innel)}(E)}{2}$$

where

$$\sigma_{\pi p}^{(innel)}(E) \approx (34.3 + 1.88L + 0.25L^2) \cdot \left(1 - \left(\frac{E_{th}}{E_p}\right)^4\right)^2 \cdot 10^{-27} cm^2$$

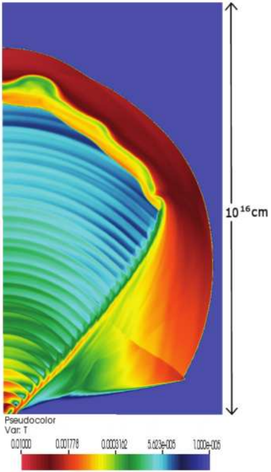
$$L = ln \frac{E_p}{1000 GeV}, E_{th} = 1.2 GeV$$

- Adiabatic Cooling:Since the jet is expanding with velocity u_b, the adiabatic cooling rate is:

$$t_{adb}^{-1} = \frac{2}{3}\frac{u_b}{z}$$

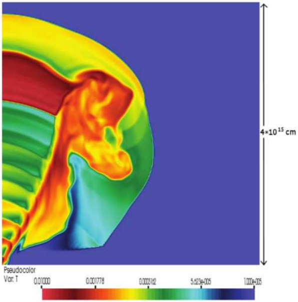
The logarithm of the Temperature T

- Two-dimensional slice from a three-dimensional simulation, depicting the logarithm of the Temperature T (units of 10^{13}K.
- The maximum temperature is 10^{11}K
- The minimum is 10^{8}K (the actual minimum is near zero).



The temperature T for the light jet case

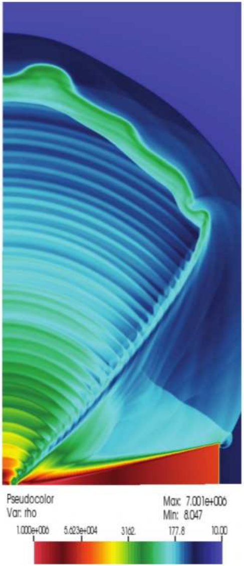
- The lighter jet advances more slowly,creating a richer cocoon and a protrusion effect just before the jet head.
- The equatorial region is also active now, albeit closer to the jet base, and it persists longer due to the slower jet expansion.



Smponias, Kosmas, Mon. Not. R. Astron. Soc. 412, 13201330 (2011)

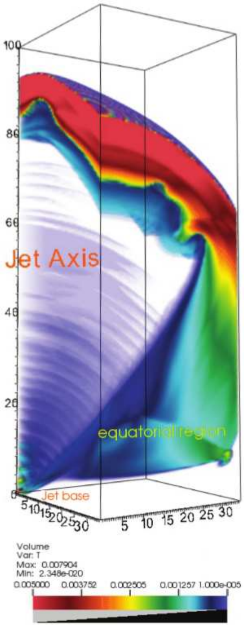
The logarithm of the temperature T for the light jet case

- A logarithmic plot of a slice of the density at model time 464, in units of proton cm^{-3}, with the same orientation as the temperature slices.
- We can see the same pattern at the equatorial region as in the previous images.
- The domain length along the jet is 10^{16} cm.



The model system of a heavy jet

- A three-dimensional view of the model system of a heavy jet at model time 464 (around 464 hr), depicting the model octant in 3D space, showing the temperature in code units of 10^{13}K.
- The domain length along the jet is 10 16 cm. The length units along the bounding-box axes are 10^{14} cm.



Smponias, Kosmas, Mon. Not. R. Astron. Soc. (2014)

Summary and Conclusions

- We study (i) High energy neutrinos and (ii) High energy γ -rays, produced (interior of the hadronic jets) through decays of secondary particles: charged particles ($\pi^{\pm}$, $K^{\pm}$, $\mu^{\pm}$, etc.) and neutral particles (π_0, η, etc.), respectively, originating from p-p collision (thermal protons on non-thermal ones) in relativistic black hole MQs.
- We focus on the neutrino emissivity from MQ hadronic jets by employing PLUTO hydro code.
- This computational tool has provided:
  (i) realistic modelling of radio and gamma-ray emission, and
  (ii) efficient estimation of neutrino emission events originating from MQ jets.
- For the observation of such neutrino fluxes, current terrestrial detectors (e.g. IceCube (at South Pole) and KM3NeT (at Mediterranean sea) are in operation.

Collaborators:

- University of Ioannina, Greece: T. Smponias, D.K. Papoulias
- Univ. of Ioannina (Dept. of Mathematics): M. Xenos
- NCSR Democritos, Greece: G. Stavropoulos, D. Balasi (KM3NeT Experiment)
- Univ. of Erlangen-Nureberg, Germany: Group of Alexander Kappes (IceCube Experiment)
- Univ. of Manchester, U.K.: O.T. Kosmas

Thank you

for your attention