Neutrino production in Population III microquasars

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Resumen / *Contexto* Los microcuásares de población III (Pop III MQs) pudieron haber sido uno de los principales contribuyentes al proceso de reionización del medio intergaláctico. Se cree que las estrellas de población III fueron formadas a corrimientos al rojo altos, aproximadamente $z \sim 20-30$, lo cual impide la posibilidad de detectar rayos gamma de muy alta energía ($E > 100$ GeV); y por lo contrario, los neutrinos podrían ser detectados en la actualidad, debido a que solo sufren interacciones débiles.
Objetivo Desarrollamos un modelo para la producción de neutrinos en Pop III MQs y comparamos el flujo difuso obtenido con los datos disponibles del telescopio de neutrinos IceCube.
Método Resolvemos ecuaciones de transporte para obtener las distribuciones de partículas en diferentes zonas consideradas a lo largo de los chorros. Calculamos las distribuciones de partículas primarias (esto es protones y electrones) en cada zona, las cuáles se enfrían debido a procesos radiativos y a la interacción con otras partículas blanco, para dar una distribución de partículas secundarias (esto es muones y piones). Luego, obtenemos las distribuciones de muones y piones y calculamos sus decaimientos, que nos permiten calcular la producción de neutrinos. Finalmente, integramos con respecto al corrimiento al rojo z y con respecto al ángulo con la visual, para obtener el flujo difuso de neutrinos que podría ser observado desde la Tierra.

Abstract / *Context* Population III microquasars (Pop III MQs) may have been one of the main contributors to the reionization of the intergalactic medium. It is thought that PopIII stars were formed at redshifts $z \sim 20-30$, which prevents the possibility of detecting gamma rays of very high energy ($E > 100$ GeV). Conversely, it would be possible to detect neutrinos at the present, since they interact with matter only via the weak interaction.
Aims We develop a model that accounts for neutrino production in Pop III MQs and compare the diffuse neutrino fluxes obtained with the available data from IceCube neutrino telescope.
Method We solve transport equations to obtain the particle distributions at the different zones considered along the jets. We compute the distributions of primary particles (i.e. protons and electrons) in each zone, which cool down due to radiative processes and also interact with other particle targets, to give a distribution of secondary particles (i.e. muons and pions). We then obtain the muon and pion distributions and compute their decays, from which we obtain a neutrino output. Finally, we integrate with respect to the redshift z and over the line-of-sight angle in order to obtain the diffuse neutrino flux that may be observed from the Earth.

Keywords / neutrinos — X-rays: binaries — stars: Population III — dark ages, reionization, first stars

1. Introduction

At the period of recombination (0.37 Myr after the Big Bang), the plasma of electrons and protons went through a phase transition that coupled them together for the first time to form atomic hydrogen. This was followed by a period commonly named as "Dark Ages", during which no structures capable of producing radiation had yet been formed. This period ended ~ 1 Gyr after the Big Bang due to the ultraviolet (UV) radiation produced by the first formed stars, and the "Epoch of Reionization" began. However, it is thought that in order to reionize the intergalactic medium (IGM), the UV radiation produced by massive stars was not enough, since the ionizing UV photons must have escaped from the primordial galaxies at higher rates than the observed. Astrophysical sources like active galactic nuclei, cosmic rays, and X-ray binaries, have been proposed as possible contributors to the reionization of the IGM. In particular, it has been suggested that Pop III microquasars (MQ) could have contributed enough radiation as required to ionize the IGM. In the present work we aim to obtain the possible neutrino emission from these systems in order to compare with current data from IceCube. The model adopted here is based in previous works on microquasar jets and their interaction with the external medium (Bordas et al., 2009; Bosch-Ramon et al., 2011; Romero & Sotomayor Checa, 2018), which allows the possibility of taking into account different zones or regions along the jet where particle acceleration and emission can take place.

2. Outline of the model

The microquasar jets are modeled considering different emission zones along them, where particles are being accelerated by some mechanism. We account for all the main interactions of particles by solving a particular transport equation corresponding to each zone, in order to finally compute a total neutrino output.

The first zone considered (base zone) is located at the inner jet, which is launched at a distance $z_0 = 100R_g$ from the central black hole (BH). The magnetic field along the jet is supposed to vary as $B = B_0(z_0/z)^{1.5}$, where z is the distance to the BH, and B_0 is the magnetic field at z_0. This implies that the magnetic energy density decreases faster than the kinetic one. We place the position of the base zone at $z_{\rm acc}$ where the kinetic energy density is in sub-partition with the magnetic energy density by a fraction q_m, i.e. $\rho_m = q_m\rho_k$, with $\rho_k = L_k/[(\Gamma - 1)\Gamma\pi R_{\rm jet}^2 v_{jet}]$. Here, $R_{\rm jet}$ is the radius of the jet and v_{jet} is its bulk velocity. Primary particles (protons and electrons) are injected as power laws in the energy. The injection as a function of the energy for the particle type i (that stands for protons or electrons) is $Q_i(E_i) = K_i E_i^{-\alpha}\exp(-E_i/E_{{\rm max},i})$, where K_i is a normalizing constant that is fixed with the luminosities L_i. The maximum energies $E_{{\rm max},i}$ are found by the balance of the cooling rates with an acceleration rate given by $t_{\rm acc}^{-1} = \eta cB/E$, where η is the acceleration efficiency. The transport equation for the primary particles distributions at the base zone $N_{i,\rm b}$ of type $i = \{e, p\}$, corresponds to a typical one-zone approximation:

$$-\frac{d(b_i N_{i,\rm b})}{dE_i} + \frac{N_{i,\rm b}}{T_{\rm esc}} = Q_i \qquad (1)$$

where $b_i \equiv dE/dt = Et_{\rm cool}^{-1}$ accounts for the continuous energy losses of particles due to the cooling processes: synchrotron, Inverse Compton (IC), adiabatic expansion, pp and $p\gamma$ interactions. The photon target for IC and $p\gamma$ interactions is considered to be given by the synchrotron emission of the electrons. The thickness of the zone is $\Delta z \sim R_{\rm jet}$, and the escape timescale in the comoving jet frame is $T_{\rm esc} \simeq \Gamma\Delta z/c$, where Γ is the Lorentz factor of the jet. Pions are generated via $p\gamma$ and pp interactions, and the corresponding injection Q_π can be computed as in (Reynoso & Romero, 2009), using approximations for the SOPHIA code for $p\gamma$ interactions (Atoyan & Dermer, 2003), and using fits based on the SIBYLL code in the case of pp interactions (Kelner et al., 2006). The pion distribution is obtained as a solution of

$$-\frac{d(b_i N_{i,\rm b})}{dE_i} + \frac{N_{i,\rm b}}{T_{\rm esc}} + \frac{N_{i,\rm b}}{T_{\rm dec}} = Q_i \qquad (2)$$

where $T_{\rm dec}$ is the typical decay time. Muons, in turn, are produced by the decay of pions, and the corresponding injection Q_μ is obtained following the above references. The muon distribution N_μ is then found solving Eq. 2 for the base zone.

For the typical values of jet power and magnetic field adopted in the present context, we found that for electrons injected at the base zone, cooling dominates over escape. Hence, all the power injected in electrons at this zone, is essentially radiated there. This is not the case for protons, which undergo a not so efficient cooling as compared to the escape. This is the main reason why it becomes necessary to consider the effect of the protons that were originally injected at the base zone but did not get to efficiently cool there, and rather escaped to continue their propagation along the jet. The second zone is then an extended conical one due to the lateral expansion of the jet as it propagates. We consider a transport equation with a convection term, which expressed in spherical coordinates reads (Zdziarski et al., 2014):

$$\frac{\Gamma v_{\rm jet}}{r^2}\frac{\partial(r^2 N_{i,\rm c})}{\partial r} - \frac{\partial(b_i N_{i,\rm c})}{\partial E} = Q_{i,\rm c}, \qquad (3)$$

where the injection term is $Q_{i,\rm c} = N_{i,\rm b}/T_{\rm esc}$. Pions are produced by pp interactions in this zone, and after computing the injection along the conical jet, we solve Eq. 3 including also a decay term to obtain the pion distribution. A similar procedure is carried out to obtain the muon distribution in this zone.

Table 1: Parameters of the model

Symbol	Description	Value
$M_{\rm bh}$	black hole mass [$M_\odot$]	30
Γ	jet Lorentz factor	1.67
L_k	jet kinetic power [erg s^{-1}]	10^{41}
ξ	jet half-opening angle [°]	5.7
$q_{\rm rel}$	ratio $(L_p + L_e)/L_k$	~ 0.07
a	ratio L_p/L_e	1
q_m	ratio ρ_m/ρ_k at $z_{\rm acc}$	0.001
B	magnetic field at $z_{\rm acc}$ [G]	4.8×10^3
α	index for injection $\propto E^{-\alpha}$	2
z_0	jet launching point [cm]	4.4×10^8
$z_{\rm acc}$	position of base zone [cm]	4.4×10^{11}
$z_{\rm rec}$	jet reconfinement point [cm]	1.2×10^{20}
$l_{\rm b}$	bow shock position [cm]	3.5×10^{20}
$t_{\rm MQ}$	maximum MQ age [yr]	10×10^5

The third zone considered is a reconfinement one, placed at a position $z_{\rm rec}$, where expansion ends due to the external pressure of the IGM (Bordas et al., 2009). This forces the cone shaped jet to become a cylinder. Since we found that a significant fraction of the relativistic protons can reach the reconfinement point by convection, we added an extra term of acceleration to Eq. 1, $b = \eta Bc$, and applied it in this reacceleration zone. The magnetic field in this and in the rest of the terminal regions of the jet were considered to represent a magnetic energy equal to 10 % of the kinetic energy density. The thickness of this zone is taken to be the jet radius at $z_{\rm rec}$, and the escaping particles are injected in a fourth zone which corresponds to the rest of the reconfined jet and extends down to the the region where the jet is finally stopped.

Two other zones are present at the terminal jet, one due to the forward shock produced by the interaction with the IGM, and the reciprocal reverse shock. These are called bow shock and cocoon, respectively and are placed at a distance $l_{\rm b}$ from the BH. This value, along with $z_{\rm rec}$ are computed following Bordas et al. (2009), and they depend on the IGM density, the jet power, and the MQ age $t_{\rm MQ}$.

3. Results

Once we have the pion and muon distributions for each zone, we obtain the different neutrino emissivities following (Lipari et al., 2007; Reynoso & Romero, 2009). The contributions are: direct pion decays to $\nu_\mu + \bar{\nu}_\mu$

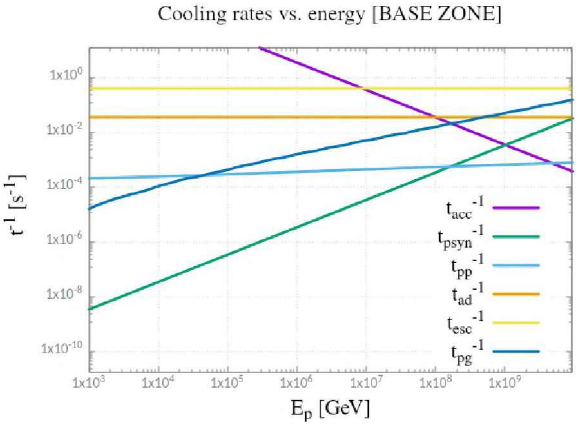

Figure 1: Acceleration and cooling rates for protons at $z_{\rm acc}$.

$(Q_{\pi\rightarrow\nu_\mu})$, muon decays to $\nu_\mu + \bar{\nu}_\mu$ $(Q_{\mu\rightarrow\nu_\mu})$, and muon decays to $\nu_e + \bar{\nu}_e$ $(Q_{\mu\rightarrow\nu_e})$.

These neutrino emissivities are in particular dependent on the viewing angle $i_{\rm j}$, and the total emission is found to depend on the length of the conical zone, which in turn depends on the MQ age $t_{\rm MQ}$ and the redshift through the IGM density. Taking this into account, and in order to estimate a total diffuse neutrino flux to be observed at present, we consider that the rate of formation of Pop III MQs as a function of the redshift is a fraction of the rate of formation of Pop III stars:

$$R_{\rm MQ} = f_{\rm BH} f_{\rm bin} R_{\rm PopIII}(z) [M_\odot {\rm Mpc}^{-3} {\rm yr}^{-1}] \qquad (4)$$

We suppose $R_{\rm PopIII}(z)$ as given by de Souza et al. (2011), and we consider that the typical mass of Pop III stars is $\sim 50 M_\odot$, a fraction $f_{\rm BH} \simeq 0.9$ of them produced BHs, and a fraction $f_{\rm bin} \simeq 0.5$ were part of a close binary system.

At a given redshift z, in order to account for the effects of having a MQ population with jets pointing at different angles i_j with the line of sight, we perform an integration over such angle. We also integrate on the possible MQ ages up to $t_{\rm MQ} \simeq 10^5$ yr, to account for the fact that the neutrino emission is not constant along the MQ life. We obtain the total neutrino spectrum for MQs at a redshift z as:

$$\frac{dN'_\nu}{dE'_\nu} = 4\pi \int_0^{\Delta V} dV \int_0^{t_{MQ}} dt_{MQ} \int_0^{\frac{\pi}{2}} di_j \sin(i_j) \times \left[Q'_{\nu_\mu} P_{\nu_\mu\rightarrow\nu_\mu} + Q'_{\nu_e} P_{\nu_e\rightarrow\nu_\mu} \right]), \quad (5)$$

where the primed variables are evaluated in a reference system at rest with respect to the BH. $P_{\nu_\mu\rightarrow\nu_\mu} \simeq 0.369$ is the probability that the generated ν_μ or $\bar{\nu}_\mu$ keep the same flavor, and $P_{\nu_e\rightarrow\nu_\mu} \simeq 0.255$ is the probability that ν_e or $\bar{\nu}_e$ oscillate into ν_μ or $\bar{\nu}_\mu$. These probabilities are derived from the unitary mixing matrix $U_{\alpha j}$, which is determined by three mixing angles: $\theta_{12} \simeq 34°$, $\theta_{13} \simeq 9°$, and $\theta_{23} \simeq 45°$ (Gonzalez-Garcia et al., 2012).

Using the neutrino spectrum, the diffuse flux originated in Pop III MQs is found as (Ando & Sato, 2004)

$$\frac{d\Phi_\nu(E_\nu)}{dE_\nu} = \frac{c}{4\pi H_0} \int_{z_{\rm min}}^{z_{\rm max}} \frac{dz\, R_{\rm MQ}(z)}{\sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3}} \frac{dN'_\nu}{dE'_\nu} (6)$$

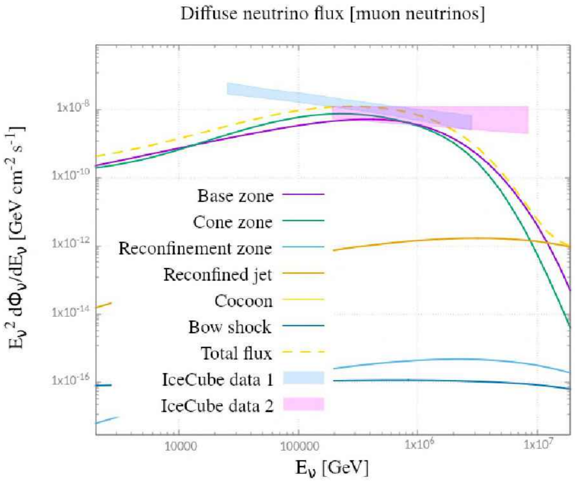

Figure 2: Diffuse flux of muon neutrinos for the different parameter set adopted.

We present some of the results obtained for a typical Pop III MQs with the parameters shown in Table 1. In Fig. 1, we show the acceleration and cooling rates for protons at the base zone, placed at a distance $z_{\rm acc}$ from the BH. In Fig. 2, we show the diffuse flux of muon neutrinos.

4. Conclusions

We have studied the consequences regarding neutrino emission of particle acceleration to relativistic energies in the jets of Pop III MQs. Using a set of parameters considered appropriate for such systems, we took into account the different zones in the jets where particle acceleration can be expected. Using transport equations, we found that the most relevant zones for neutrino production in the jets are the jet base and the conical jet zone. Finally, with the aid of an estimate for the rate of formation of Pop III stars, we obtained a rate of formation of Pop III MQs as a function of the redshift, and we integrated the diffuse neutino flux that can be at the level of the IceCube data.

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