structured jets in bl lac objects: efficient pev neutrino factories?

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ABSTRACT

The origin of high-energy neutrinos (0.1–1 PeV range) detected by IceCube remains a mystery. In this work, we explore the possibility that efficient neutrino production can occur in structured jets of BL Lac objects, characterized by a fast inner spine surrounded by a slower layer. This scenario has been widely discussed in the framework of the high-energy emission models for BL Lac objects and radio galaxies. One of the relevant consequences of a velocity structure is the enhancement of the inverse Compton emission caused by the radiative coupling of the two zones. We show that a similar boosting could occur for the neutrino output of the spine through the photo-meson reaction of high-energy protons scattering off the amplified soft target photon field of the layer. Assuming the local density and the cosmological evolution of γ-ray BL Lac object derived from Fermi Large Area Telescope data, we calculate the expected diffuse neutrino intensity, which can match the IceCube data for a reasonable choice of parameters.

Key words: BL Lacertae objects: general – gamma rays: galaxies – neutrinos

Online-only material: color figures

1. INTRODUCTION

The origin of high-energy neutrinos with energies 100 TeV–few PeV detected by IceCube (Aartsen et al. 2013, 2014) remains a mystery (see, e.g., Anchordoqui et al. 2014 for a review). The flux level is very close to that expected from the emission by photo-meson reactions in optically thin UHECR (E > 10^19 eV) sources (Waxman & Bahcall 1999), but the energies of the neutrinos link them to parent cosmic rays (CR) with much smaller energies E ~ 10^{16}–10^{17} eV. The measurements are consistent with an isotropic, ν_e : ν_μ : ν_τ = 1 : 1 : 1 flux with slope E^{-2}, but the absence of events above 2 PeV and, in particular, at the Glashow resonance for ν_e at 6.3 PeV, compellingly suggests a break or a cutoff in the spectrum close to 1 PeV (e.g., Anchordoqui et al. 2014).

Among all possible astrophysical sources of high-energy neutrinos, radio-loud active galactic nuclei have been widely considered in the past. In particular, attention has generally been focused on blazars, i.e., those whose relativistic jets point toward the Earth. These sources dominate the high-energy γ-ray sky, both at GeV and TeV energies. Their powerful, relativistically boosted, non-thermal continuum ranging from the radio band to γ-ray energies is produced within the jet by ultra-relativistic particles. The most popular scenario assumes that the emission is entirely due to leptons through synchrotron and inverse Compton (IC) mechanisms (e.g., Ghisellini et al. 1998). Alternatively, hadronic models postulate that the high-energy emission originates from ultra-high-energy hadrons, emitting through synchrotron or photo-meson mechanisms (e.g., Mücke et al. 2003). Even if hadrons are not the dominant source of high-energy radiation, their interaction with the radiation fields naturally results in the emission of neutrinos.

Recently, Murase et al. (2014) and Dermer et al. (2014) performed a thorough analysis of the expected neutrino emission through photo-meson reactions in blazar jets under the assumption that an important CR component exists in the jets of all kind of blazars. Their results show that neutrino output is dominated by the most powerful blazars (flat spectrum radio quasar; FSRQ) with a marginal contribution by the weak blazars, the so-called BL Lac objects. Besides the low intrinsic power of the jet, the inefficient neutrino production by BL Lac objects is a direct consequence of the small radiation energy density in these jets. The integrated neutrino spectrum of Murase et al. (2014), however, is expected to have a maximum—strictly linked to the peak frequency of the soft target radiation field—occurring at relatively high energies, above 10 PeV. Murase et al. (2014) concluded that it is difficult to reproduce the IceCube results with the simplest emission model without invoking complications to the standard scenario.

On the observational side, an interesting clue has recently been provided by Padovani & Resconi (2014), who, through a correlation analysis of IceCube events and gamma-ray sources, find a suggestive positional correlation of some events with few “classical” TeV BL Lac objects, most notably Mkn 421, PG 1553+113, and H 2356-309 (other events instead seem to be correlated with pulsar wind nebulae in the Milky Way).

Motivated by these hints, we reconsider here the possible production of neutrinos in BL Lac object jets. The aforementioned analysis by Murase et al. (2014) and Dermer et al. (2014) is based on the standard one-zone emission framework, assuming that a single active sub-region of the jet is responsible for the bulk of the radiation that we observe from blazars. However, there is growing evidence that the emission occurs in more complex regions. In particular, the modeling of the emission of TeV emitting BL Lac objects and low power radio-galaxies (thought to be the misaligned parent population of BL Lac objects; e.g., Urry & Padovani 1995) led us to postulate the existence of a structure for the jet, with a faster core (the spine) surrounded by a slower layer (Ghisellini et al. 2005; Tavecchio & Ghisellini 2008). Such a spine-layer structure is actually directly inferred from very long baseline interferometry observations in the radio band, showing a “limb-brightened” structure of some jets, whose simplest explanation is a transverse velocity...
structure of the jet (e.g., Giroletti et al. 2008). The basic idea of the spine-layer model is that such a structure naturally implies the enhancement of the radiative output of both components. In fact, due to the relativistic amplification induced by the relative motion, the radiation produced by one component can dominate the radiation field in the frame of the other, leading to an overall increased efficiency of the IC emission with respect to that of the one-zone model. Clearly, the same principle can be applied to the production of neutrinos, whose emission through photo-meson production by high-energy protons in the spine can be boosted by the amplification of the layer radiation field in the spine frame. Although all BL Lac objects could be characterized by a spine-layer structure, we focus here only to the so-called highly peaked BL Lac objects (HBL; the majority of the TeV emitting BL Lac objects), for which the spine-layer structure has been observed directly. As discussed by Murase et al. (2012), protons can in principle be accelerated in these jets up to maximal energies of \( E \approx 10^{19} \) eV, much more than those required to produce PeV neutrino energies.

Given the exploratory nature of this work, we do not try a completely self-consistent modelization of the photon and neutrino emission. Rather, we adopt a template for the spectrum of the layer inspired by the observed spectral energy distribution (SED) of HBL and previous application of the structured jet model. We leave a more detailed study to future work.

Throughout the Letter, we assume a cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.3 \), \( \Omega_\Lambda = 0.7 \).

2. THE MODEL

2.1. Structured BL Lac Object Jets

We briefly recall the basic features of the structured jet framework of Ghisellini et al. (2005) relevant for the present application.

The jet is modeled as a two-fluid flow, with a spine with a bulk Lorentz factor \( \Gamma_s \) and an outer layer with a bulk Lorentz factor \( \Gamma_l < \Gamma_s \). Observing the jet at a viewing angle \( \theta_i \), the spine and the layer are characterized by a relativist Doppler factor \( \delta_i = [\Gamma_i(1 - \beta_i \cos \theta_i)]^{-1} \), \( Q, Q' \) and \( Q'' \) indicate quantities measured in the observer, spine, and layer reference frame.

The (soft) target radiation field of the layer in the observer frame is parameterized by a smoothed broken power-law function:

\[
L_i(\epsilon) = \frac{k}{\epsilon_0} \left( \frac{\epsilon}{\epsilon_0} \right)^{-\alpha_1} \left[ 1 + \left( \frac{\epsilon}{\epsilon_0} \right)^{-\alpha_2} \right], \tag{1}
\]

whose normalization is given by the total observed luminosity \( L_i = \int L_i(\epsilon) d\epsilon \). The corresponding photon number density in the layer frame is

\[
n''(\epsilon_i) = \frac{L_i(\epsilon)}{4\pi R^2 C_0 \delta_i \epsilon_i}, \tag{2}
\]

where \( \epsilon_i = \epsilon / \delta_i \) and \( R \) is the jet radius.

The relative motion of the two components leads to the amplification of the radiation field of the layer as observed in the spine reference frame (and vice versa). Specifically, given the number density of the soft radiation in the layer frame, the photon density in the spine frame is \( n''(\epsilon_i') d\epsilon_i' = \Gamma_{rel} n''(\epsilon''_i) d\epsilon''_i \), where \( \Gamma_{rel} = \Gamma_s \Gamma_l / (1 - \beta_s \beta_l) \) is the relative Lorentz factor and \( \epsilon_i' \simeq \Gamma_{rel} \epsilon_i'' \). Note that while the relevant quantity for the IC emission is the energy density of the target photon field (i.e., the synchrotron radiation produced in the layer), which transforms as \( \Gamma_{rel}^2 \), here we are interested to the numerical density, depending on \( \Gamma_{rel} \). For simplicity (as in Atoyan & Dermer 2003), we do not take into account the fact that the radiation field of the layer in the spine frame (dominating the photo-meson reactions) is anisotropic (Dermer 2003), we do not take into account the fact that the relative motion of the two components leads to the fact that the radiation field in the frame of the other, leading to an overall increased efficiency of the IC emission with respect to that of the one-zone model. Clearly, the same principle can be applied to the production of neutrinos, whose emission through photo-meson production by high-energy protons in the spine can be boosted by the amplification of the layer radiation field in the spine frame. Although all BL Lac objects could be characterized by a spine-layer structure, we focus here only to the so-called highly peaked BL Lac objects (HBL; the majority of the TeV emitting BL Lac objects), for which the spine-layer structure has been observed directly. As discussed by Murase et al. (2012), protons can in principle be accelerated in these jets up to maximal energies of \( E \approx 10^{19} \) eV, much more than those required to produce PeV neutrino energies.

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Throughout the Letter, we assume a cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.3 \), \( \Omega_\Lambda = 0.7 \).

2.2. Neutrino Emission

We assume that in the spine there is a population of CR (protons) whose luminosity (measured in the spine frame) is parameterized by a cut-offed power-law distribution:

\[
L'_p(E'_p) = k_p E'_p^{-\alpha} \exp \left(- \frac{E'_p}{E'_{cut}} \right) \quad E'_p > E'_{\text{min}} \tag{3}
\]

with a total (spine frame) luminosity \( L'_p = \int L'_p(E'_p) dE'_p \).

The neutrino yield (in the spine frame) through the decay of the pions produced by the photo-pion reactions of protons, \( \pi^0 \rightarrow \mu^+ \mu^- + 2\nu_e + \bar{\nu}_e \) (we do not distinguish among \( \nu \) and \( \bar{\nu} \)), is parameterized (e.g., Murase et al. 2014) by \( f_{\nu}(E_p) = \frac{n_{dyn}}{t_{\nu}(E'_p)} \), in which \( n_{dyn} \approx R/c \) is the dynamical timescale and the (inverse of) the photo-meson cooling time is given by

\[
t_{\nu}^{-1}(E'_p) = c \int_{E_{in}}^{\infty} d\epsilon_p \frac{n''(\epsilon)}{2\epsilon_p^2} \int_{E_{in}}^{2\epsilon_p''} d\epsilon' \sigma_{\nu \gamma}(\epsilon') K_{\nu \gamma}(\epsilon') \epsilon', \tag{4}
\]

where \( \gamma''_p = E'_p / m_p c^2 \), \( \sigma_{\nu \gamma}(\epsilon) \) is the photo-pion cross section, \( K_{\nu \gamma}(\epsilon) \) the inelasticity, and \( E_{in} \) is the threshold energy of the process. We evaluate the integrals in Equation (4) using the simple but accurate prescription for \( \sigma_{\nu \gamma} \) and \( K_{\nu \gamma} \) provided in Atoyan & Dermer (2003), including both single-pion (from the \( \Delta^+ \) resonance) and multi-pion reactions. Since, as we verify below, the target radiation field in the spine reference frame is dominated by the beamed layer component, we only consider it in the integral.

The resulting neutrino luminosity in the spine frame is given by (e.g., Murase et al. 2014):

\[
E'_i L'_i(E'_i) \approx \frac{3}{8} f_{\nu}(E'_p) E'_p L'_p(E'_p); \quad E'_i = 0.05 E'_p, \tag{5}
\]

where the factor 3/8 takes into account the fraction of the energy going into \( \nu \) and \( \bar{\nu} \) (of all flavors). For completeness, we also calculate the luminosity of photons (from the \( \pi^0 \rightarrow 2\gamma \) decay), using the same equation and a factor of 1/2 instead of 3/8. The contribution of the possible synchrotron emission of CR is negligible (e.g., Tavecchio 2014).

Finally, we calculate the neutrino (and the photon) luminosity in the observer frame using the standard transformations: \( E_{\nu} L_{\nu}(E_{\nu}) = E'_i L'_i(E'_i) \delta^2_i \) and \( E_{\nu} = \delta_i E'_i \).

2.3. Diffuse Intensity

The procedure described in the previous section allows us to derive the neutrino output from a single BL Lac object. The cumulative diffuse emission from a population of BL Lac objects, each one emitting a neutrino luminosity as calculated above, is determined using

\[
E_{\nu} I(E_{\nu}) = \frac{c}{4\pi H_0} E_{\nu}^2 \int \frac{j(E_{\nu}(1 + z), z)}{\sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda}} dz, \tag{6}
\]
in which the comoving volume neutrino emissivity is given by the product of the comoving density of sources $\Sigma(z)$ and the source neutrino luminosity

$$j(E_\nu, z) = \Sigma(z) \frac{L_\nu(E_\nu)}{E_\nu}.$$  

(7)

The cosmological evolution of $\gamma$-ray emitting blazars has recently been studied by Ajello et al. (2014) using Fermi Large Area Telescope data. As already noted, we will focus our calculations on HBL, the majority of the TeV emitting BL Lac objects. Local HBL show a negative evolution, i.e., $\Sigma(z)$ decreases with $z$. Although complex relations are used by Ajello et al. (2014) to model the luminosity-dependent evolution of the blazar density, here, for simplicity, we parameterize the evolution of the HBL as; $\Sigma(z) = \Sigma_0 (1+z)^{-\beta}$. From Figure 10 of Ajello et al. (2014), one infers $\Sigma_0 \simeq 2 \times 10^{-7}$ Mpc$^{-3}$ and the fast decrease of the density is reproduced by $\beta \sim 6$ (we checked that the results are only weakly dependent on the precise value of $\beta$).

A similar calculation provides the expected flux of CR from HBL, assuming that they can efficiently escape from the jets and are not substantially deviated by magnetic fields. For the energies of interest here ($E_p < 10^{18}$ eV) and for local sources such as HBL, the propagation losses are negligible (e.g., Berezinsky et al. 2006). If we allow the CR to escape from the jet, the CR cumulative flux is limited by the observed flux at Earth.

3. RESULTS

In summary, the free parameters of the model are the jet radius, $R$, the spine and layer Lorentz factors, $\Gamma_s$ and $\Gamma_l$, the observed layer luminosity, $L_s$, and its peak energy, $E_o$, the spectral slopes, $\alpha_1$ and $\alpha_2$, the spine comoving CR luminosity, $L_p^s$, the CR power-law index, $n$, and the minimum and the cut-off energy, $E_{\text{min}}^\nu$ and $E_{\text{cut}}^\nu$.

The choice of the values of some parameters is guided by the results of the modeling of HBL emission. For definiteness, we fix the jet radius to $R = 10^{15}$ cm (e.g., Tavecchio et al. 2010), $\Gamma_s = 15$, $\Gamma_l = 2$, and $\delta_t = 20$. Consequently, $\delta_1 = 3.7$ and $\Gamma_{\text{rel}} = 4$. The observed luminosity of the low-energy emission component of the layer is constrained from above, since we demand that the observed SED of HBL is dominated by the spine. For the low- and high-energy slopes we assume the customary values $\alpha_1 = 0.5$ and $\alpha_2 = 1.5$. For the spine SED we adopt a template the SED of the prototypical HBL Mrk 421 calculated in Tavecchio et al. (2010).

The remaining free parameters are $L_s$, $E_o$—determining the layer target photon spectrum—and $L_p^s$, $E_{\text{min}}^\nu$, $E_{\text{cut}}^\nu$, and $n$—specifying the CR spectrum. Adjusting these parameters, we can find the best solution reproducing the IceCube measurements, which are reported in Figure 1 (red and gray data points, from Aartsen et al. 2014). We report two possible cases (models 1 and 2). For both we assume $n = 2.5$ and we assume a CR flux level comparable to the observed one (since the neutrino luminosity is proportional to the product of the CR luminosity and the density of target photons, one could relax this assumption allowing a larger luminosity for the layer). The other parameters are listed in Table 1.

In the first case (model 1, dashed line in Figure 1), we assume that the spectrum lies below the IceCube upper limit around 1 PeV, thus implying that the neutrinos with $E_\nu < 1$ PeV belong to a separate component (see, e.g., He et al. 2013). This condition, together with the upper limit at 10 PeV, implies a quite narrow spectrum. In the second case (model 2, solid line), we relax this condition, allowing a single component to describe the entire spectrum. In both cases, the neutrino flux is supposed to cut off in correspondence to the upper limit at 10 PeV, a constraint that fixes the maximum CR energy.

The main difference between the two cases is the peak energy of the layer component, $E_o$ and $E_{\text{min}}^\nu$. The effect of these parameters can be understood recalling the relation linking the neutrino energy to that of the parent CR, $E_\nu \simeq 0.05 E_p$, and the threshold condition for pion production, $E_p^\nu > m_\pi m_p c^2$. To increase the flux at low energy, one must thus decrease $E_{\text{min}}^\nu$ (decreasing the energy of the produced neutrinos), at the same time increasing $E_o$ (to satisfy the threshold). In turn, decreasing the minimum CR energy leads to the increase of the total CR power (dominated by the low-energy particles). This explains the different parameters of the two cases.

We recall that at energies below $\sim 300$ TeV, one expects the possible contribution from a hard atmospheric prompt component, the actual level of which is, however, still uncertain. The gray data points in Figure 1 display the extraterrestrial flux for an increased flux of the prompt component to the level of the 90% CL limit (Aartsen et al. 2014). Model 2 is in full agreement with these high-background data.

Figure 2 shows the luminosities in the observer frame of the different components for the two models. Besides the spine emission, the low-energy emission of the layer, neutrinos

## Table 1

| Model | $L_s$ (erg s$^{-1}$) | $E_o$ (eV) | $L_p^s$ (erg s$^{-1}$) | $E_{\text{min}}^\nu$ (eV) | $E_{\text{cut}}^\nu$ (eV) |
|-------|---------------------|-----------|-----------------------|-------------------------|------------------------|
| 1     | $1.9 \times 10^{44}$ | 2.5       | $2.5 \times 10^{42}$  | $2 \times 10^{12}$     | $2.3 \times 10^{15}$   |
| 2     | $1.9 \times 10^{44}$ | 410       | $1.8 \times 10^{43}$  | $3 \times 10^{10}$     | $2 \times 10^{15}$     |
photon reaction.

Considering the derived neutrino luminosity, one can also calculate the expected number of events from a single source. Convolving the IceCube effective area with the flux derived with our model (as, e.g., Yacobi et al. 2014) from a source at $z = 0.03$ (like the prototypical HBL Mkn 421 and Mkn 501), we found that with three years of exposure one should detect one neutrino for model 1 and four neutrinos for model 2. Interestingly, this value is compatible with the findings of Padovani & Resconi (2014). Also comparable is the gamma-ray/neutrino luminosity ratio for Mkn 421 in our Figure 2 and their Figure 1.

We stress that we have only considered only HBL in this work, for which the existence of a layer is well assessed. The possible presence of a layer with similar properties in the jets of other BL Lac objects (IBL and LBL) or even in FSRQ could lead to an important contribution of these sources to the observed neutrino flux. A similar remark concerns the possible neutrino emission of weak Fanaroff–Riley I (FRI) radio galaxies, recently considered by Becker Tjus et al. (2014). In the blazar unification scheme, FRI radio galaxies are the misaligned versions of BL Lac objects. In the framework of the structure jet model, the emission from their jets is expected to be dominated by the (slightly) Doppler boosted emission of the layer, since the spine flux is, at large enough $\theta_z$, de-boosted by the relativistic Doppler effect. The amplification of the photo-meson luminosity induced by the spine-layer radiative interplay is expected to also occur for the layer—the spine radiation field being amplified in the layer frame. The luminosity emitted by a single radio galaxy is expected to be much lower than that of a blazars, but this is partly compensated by the (expected) larger number of sources. Therefore, one can speculate that the IceCube flux, similar to the $\gamma$-ray background, could contain the contribution from both aligned (blazars) and misaligned sources (radio galaxies).

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4. DISCUSSION

Our calculations demonstrate that a velocity structure of BL Lac object jets leads to an effective boosting of the neutrino emission with respect to the one-zone scenario. The IceCube measurements can be reproduced assuming a layer luminosity and a CR flux compatible with the observations.

Some caveats are, however, in order. The budget output of the spine is strongly unbalanced toward CR. In fact, the beaming-corrected power in radiation is $P_{\text{rad}} = L_{\text{rad}}/\Gamma_s^2 = 2.4 \times 10^{43}$ erg s$^{-1}$ for both models, while that in CR, $P_{\text{CR}} = L_{\text{CR}}/\Gamma_s^2$, is $P_{\text{CR}} = 10^{45}$ erg s$^{-1}$ for model 1 and $P_{\text{CR}} = 7.2 \times 10^{45}$ erg s$^{-1}$ for model 2, implying a ratio of $P_{\text{CR}}/P_{\text{rad}} = 41$ and 300, respectively (similar to Murase et al. 2014). To sustain such a power, the total jet power $P_{\text{jet}}$ must be larger (or at least equal) to that in the CR component. A similar result is derived comparing the CR emissivity of our model, which is of the order of several $10^{47}$ erg Mpc$^{-3}$ yr$^{-1}$, with the $\gamma$-ray emissivity of BL Lac objects (e.g., Dermer & Razzaque 2010) which is $< 10^{47}$ erg Mpc$^{-3}$ yr$^{-1}$ and probably not exceeding $2-3 \times 10^{46}$ erg Mpc$^{-3}$ yr$^{-1}$ for low-$\gamma$ BL Lac objects. Note that the “curving proton” model of Dermer et al. (2014) should allow much smaller CR powers.

Another issue is related to the fact that, while we assume that CR accelerated in BL Lac object jets dominate at $10^{16}$ eV, the standard view posits that their origin is galactic (e.g., Antoni et al. 2005). This difficulty could be avoided if CR cannot efficiently escape from BL Lac object jets/environment or outflowing winds prevent CR of these energies to penetrate into our Galaxy.

Considering the derived neutrino luminosity, one can also calculate the expected number of events from a single source. Convolving the IceCube effective area with the flux derived with our model (as, e.g., Yacobi et al. 2014) from a source at $z = 0.03$ (like the prototypical HBL Mkn 421 and Mkn 501), we found that with three years of exposure one should detect one neutrino for model 1 and four neutrinos for model 2. Interestingly, this value is compatible with the findings of Padovani & Resconi (2014). Also comparable is the gamma-ray/neutrino luminosity ratio for Mkn 421 in our Figure 2 and their Figure 1.

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