

Neutrinos from photo-hadronic interactions in Pks2155-304

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Abstract. The high-peaked BL Lac object Pks2155-304 shows high variability at multiwavelengths, i.e. from optical up to TeV energies. A giant flare of around 1 hour at X-ray and TeV energies was observed in 2006 [1]. In this context, it is essential to understand the physical processes in terms of the primary spectrum and the radiation emitted, since high-energy emission can arise in both leptonic and hadronic processes. In this contribution, we investigate the possibility of neutrino production in photo-hadronic interactions. In particular, we predict a direct correlation between optical and TeV energies at sufficiently high optical radiation fields. We show that in the blazar Pks2155-304, the optical emission in the low-state is sufficient to lead to photo-hadronic interactions and therefore to the production of high-energy photons.

Keywords: neutrinos, Pks2155-304, photo-hadronic interactions

I. VERY HIGH-ENERGY EMISSION FROM BLAZARS

The very first detection of a blazar at TeV photon energies happened in 1992, when Mkn421 was observed with the HEGRA telescopes [16]. Since then, large progress has been made detecting more and more active galactic nuclei (AGN) with detailed spectral features. As of today, 24 blazars as well as 2 radio galaxies of Fanaroff-Riley type¹ are known to emit at very high-energy (VHE), i.e. $E_\gamma > 100$ GeV). Blazars typically show a spectrum with a double-hump structure, i.e. a low-energy peak at radio to optical wavelengths and a high-energy peak at X-ray to TeV energies. The entire emission is believed to arise in the relativistic shock fronts in AGN jets, where charged particles are accelerated to ultra high-energies (UHE). The low-energy component is then due to synchrotron radiation by the accelerated electrons. Several processes can produce VHE radiation: With relativistic electrons accelerated in the shock fronts of the blazar's jet, synchrotron photons are produced. The latter are scattered to VHE via the Inverse Compton process with the primary electrons. Hadronic Cosmic

Rays (CR) are believed to be accelerated along with the electrons, up to 10^{21} eV [15], [6]. These CRs can radiate at VHE through synchrotron radiation, or interactions with ambient matter or photon fields. Here, we consider the possibility of CR interactions with photon fields.

Blazars are observed to be highly variable at all wavelengths. The source of this variability is still under discussion, ranging from instabilities in the accretion disk, see e.g. [20], to precession of the jet, see e.g. [10]. Other explanations are jets with density inhomogeneities or turbulent jets, see [17] and references therein. Such phenomena lead to the variation of the flux at low energies (between radio and X-ray). The variability at the higher energies (X-ray to TeV energies) depends on the VHE radiation origin:

- 1) *Inverse Compton scattering* can arise in two different scenarios: On the one hand, it can be due to the interaction between the accelerated electrons with the synchrotron photon field ("Synchrotron Self Compton", SSC). This leads to a direct correlation between the low- and high-energy humps of the spectrum. On the other hand, if external photons are boosted to VHE by electrons, such a correlation is not necessary. The high-energy hump would then show a variability uncorrelated to the low-energy spectrum.
- 2) *Hadronic interactions* can lead to the production of VHE photons through the production of π^0 , as neutral pions decay into two VHE photons. Here, a correlation between the low- and high-energy hump is not necessary. It can, however, be present if the hadronic Cosmic Rays interact with the synchrotron photon field itself. In the case of proton-proton interactions, no correlation would be present. In addition, synchrotron proton radiation can contribute at VHE.
- 3) *A combination of hadronic and leptonic VHE emission* is likely to be present in many cases, as protons and electrons are co-accelerated in the jet's shock fronts. The continuous interaction of the different radiation fields and charged particle populations may lead to a series of loops of VHE production. This may lead to a strongly non-linear

¹The radio galaxies are M 87 and Cen A, see [19] for a complete list of known sources

correlation between the intensity of different wavelengths. A description of repeated leptonic loops is given in [12]. The same mechanism works for hadronic loops or a combination of both, always assuming a low-energy target photon field.

As the synchrotron field from primary electrons is a good target for Inverse Compton scattering, a direct correlation between low- and high-energy photons is usually interpreted as such. In so-called orphan flares, a strong variability at VHE is observed in the absence of low-energy variability. This in turn is often taken to be an indication as a result of hadronic interactions, as these do not require an intensity change at low energies. In this paper, we present a model where variability at low-energies leads to a correlated signal at high-energies.

II. PHOTO-HADRONIC INTERACTIONS IN BLAZARS

When CRs are accelerated to UHE, they can interact with the present photon fields via the Δ -resonance:

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\pi^0 \\ n\pi^+ \end{cases} \quad (1)$$

The decay of the Δ -resonance leads to the production of charged and neutral pions, which decay into high-energy neutrinos and photons, respectively (see e.g. [3]):

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu, \text{ 1/3 of the cases} & (2) \\ \pi^0 &\rightarrow \gamma\gamma, \text{ 2/3 of the cases.} & (3) \end{aligned}$$

The probability for π^+ production is 1/3, while π^0 are produced in 2/3 of the cases. Around 1/5 of the proton energy goes into the pion, and the decay products carry equal energy, so that a fraction of 0.25 (0.5) is transferred to each neutrino (photon). Furthermore, we need to consider that the neutrinos oscillate from 2 muon neutrinos and one electron neutrino to one electron, one muon and one tau neutrino. Considering these factors, the high-energy photon- and neutrino spectra are connected as²

$$\frac{dN_\nu}{dE_\nu} \approx \frac{1}{8} \cdot \frac{dN_\gamma}{dE_\gamma}. \quad (4)$$

Photo-hadronic interactions occur under the following conditions:

- 1) Protons need to be accelerated to sufficiently high energies.
- 2) The photon field must be dense enough for the protons to interact, i.e. we need an optical depth for proton-photon interactions of $\tau_{p\gamma} \sim 1$ or larger.

The first condition is believed to be fulfilled, as AGN jets enable proton acceleration up to 10^{21} eV, see e.g. [15], [6]. An approximation of the optical depth for photo-hadronic interactions in knots of blazars is given in [4],

$$\begin{aligned} \tau_{p\gamma} \approx 0.9 &\cdot \left(\frac{10}{\Gamma}\right) \cdot \left(\frac{\theta}{0.1}\right) \cdot \left(\frac{\epsilon_{\text{knot}}}{0.1}\right) \cdot \left(\frac{L_\gamma}{10^{40} \text{ erg/s}}\right) \\ &\cdot \left(\frac{z_j}{3000 r_g}\right)^{-1} \cdot \left(\frac{\nu}{1 \text{ GHz}}\right)^{-1}. \end{aligned} \quad (5)$$

²for a detailed description, see [11].

Here, L_γ is the luminosity observed from the blazar at a given frequency ν . Further, $\Gamma \approx 10$ is the Lorentz factor of the shock and $\theta \approx 0.1$ is the jet's opening angle. The parameter ϵ_{knot} gives the fraction of luminosity coming from a single knot in the jet. The value $\epsilon_{\text{knot}} = 0.1$ indicates that the luminosity comes from 10 knots, which is the order of magnitude to be expected. Finally, z_j is the distance of the knot along the jet. The first shock is expected to be present at around 3000 gravitational radii, r_g from the foot of the jet [14]. As the optical depth drops with the distance from the center and we need those strong shocks to have efficient neutrino production, this first strong shock provides the best environment for the production of secondaries. The flaring time scale of Pks2155-304 also suggests that the emission happens in a compact region, underlining the fact that it could be due to photohadronic interactions.

III. MULTIWAVELENGTH OBSERVATIONS OF PKS2155-304

Pks2155-304 is a blazar at a redshift $z = 0.116$, located in the southern hemisphere, at (RA, Dec) = (21h58'52.0'', -30°13'32'') in J2000 coordinates [9]. It was the 5th source reported at γ -rays [7], with a steady-state emission of around 20% of the Crab nebula. Pks2155-304 shows a very rapid variability, with extreme flares, the most intense one observed in 2006 [1], with an increased intensity of more than one order of magnitude at TeV energies. This extraordinary flare lasted about 60 minutes and showed a peak intensity of 7 times the Crab nebula. CANGAROO-III was triggered by the H.E.S.S. observations and detected the flaring state at complementary times [18]. During this flaring state, no other wavelength bands were observed.

In a later flare, a multiwavelength campaign of Chandra and H.E.S.S. was started to study the correlations between the different wavelength bands [8]. Here, X-ray and TeV variabilities were more moderate, i.e. within a factor of 3, and optical emission varied within a factor of 2. For this flare, it could be shown that TeV and X-ray luminosities seem to be connected as [8]

$$L_{\text{TeV}} \propto L_{\text{X-ray}}^3. \quad (6)$$

The low-state of Pks2155-304 was monitored in a multiwavelength campaign in 2008 [2]. Four wavelength bands were observed simultaneously, namely at optical (ATOM), X-ray (RXTE & Swift), 100 MeV to 100 GeV (Fermi-LAT) and > 200 GeV (H.E.S.S.) energies. While a strong correlation between optical and VHE emission was found, X-ray energies do not correlate with the highest energies. The spectral index behavior observed by Fermi is around $E^{-2 \pm 0.5}$.

IV. NEUTRINOS FROM THE LOW-STATE OF PKS2155-304

Given the observation of the low-state of Pks2155-304 in 2008 [2], we can calculate the optical depth for photo-hadronic interactions. Here, we consider photons from

the R-band as the main target photon field. Using that the frequency of the R-band photons is $\nu = 4.6 \cdot 10^5$ GHz, the photo-hadronic optical depth becomes

$$\tau_{p\gamma_{\text{opt}}} \approx 0.6 \cdot \left(\frac{L_{\text{opt}}}{3 \cdot 10^{45} \text{ erg/s}} \right) \cdot \left(\frac{z_j}{3000 r_g} \right)^{-1} \cdot \left(\frac{\nu}{4.6 \cdot 10^5 \text{ GHz}} \right)^{-1}, \quad (7)$$

using a flow boost factor of $\Gamma = 10$. Here, we calculate the optical luminosity from the observed flux, F_{opt} , given by ATOM measurements and from the distance of Pks2155-304, d_L , is given by the blazar's redshift³,

$$L_{\text{opt}} = 3 \cdot 10^{45} \cdot \left(\frac{F_{\text{opt}}}{10^{-10} \text{ erg/s/cm}^2} \right) \text{ erg/s}. \quad (8)$$

Given Equ. (7), we can derive the optical depth for proton-photon interactions during the low-state observation of Pks2155-304. Given an average flux in the R-band of $\sim 1.1 \cdot 10^{-10}$ erg/cm²/s, the mean optical depth is $\sigma_{p\gamma_{\text{opt}}} \sim 0.7$. Considering B- and V-bands would increase the optical depth further. With these values close to unity, the observed flux of VHE photons can be due to proton interactions with optical photons. The observed correlation between R-band and TeV emission can therefore be interpreted as a result of photo-hadronic interactions.

Given an optical depth of around unity, and assuming VHE photons to come from photo-hadronic interactions, we can calculate the resulting neutrino flux for the low-state of Pks2155-304 using Equ. (4). Here, we use the Fermi measurements as a reference flux. The reason for not using H.E.S.S. measurements is that here, we can expect to see effects like absorption, while the spectrum as observed by Fermi should be unaffected. The spectral behavior as observed by Fermi, close to $dN_\gamma/dE_\gamma \propto E^{-2}$, seems to mirror the primary spectrum and can therefore be interpreted as unaffected [15], [5]. The resulting neutrino flux is given as the black, solid line in Fig. 1. Also shown is the predicted 1-year sensitivity for KM3NeT, a cubic kilometer sized neutrino detector planned to be instrumented in the Mediterranean Sea. Within only one year of operation, KM3NeT will be sensitive to the permanent neutrino flux from Pks2155-304.

A. Flux variability in high-energy photons and neutrinos

In the previous section, we investigated the possible neutrino flux from Pks2155-304 in the low-state. This component should be present permanently. The extreme variability of this source at the highest energies indicates that, in addition to this permanent component, one can expect an enhanced contribution during the time of flaring states. We investigate this fact at the example of the giant flare of Pks2155-304 observed by the H.E.S.S. experiment in 2006 [1]. Here, the VHE flux of Pks2155-304 showed increased activity by a factor of ~ 10 for

about one hour. If we assume that the VHE emission is due to photo-hadronic interactions, we can calculate the corresponding neutrino flux according to Equ. 4. The result is shown as the dotted lines in Fig. 1. The flat line corresponds to an E^{-2} primary spectrum [15], while the steep line shows an $E^{-2.3}$ primary spectrum [5]. The neutrino emission, just as the VHE photon component, is higher by approximately a factor of ten compared to the low-state.

Even in this flaring state, the increased intensity can arise from an enhanced optical emission. On the other hand, X-ray luminosities are observed to be coupled to the VHE luminosity with a correlation of $L_{\text{VHE}} \propto L_{\text{X-ray}}^3$ [8]. The question is how to explain this very strong dependence of the VHE emission with the X-ray signal. One option is the production of VHE radiation in several loops of interactions as discussed in [12], The VHE luminosity is assumed to be produced by a series of n loops of interactions between the primary electrons and the secondary synchrotron photons,

$$L_{\text{VHE}} = L_{\text{synch}} \cdot \sum_{i=1}^n x^i, \quad (9)$$

Here, L_{synch} is the synchrotron radiation field and $x = L_{\text{VHE},0}/L_{\text{synch}}$. If the initially produced VHE radiation $L_{\text{VHE},0}$ is larger than the synchrotron field, the series diverges for infinite loops $n \rightarrow \infty$. However, if the VHE radiation is cutoff at some point when going into the Klein-Nishina limit, we have a maximum number n which can be small. If this happens at $n = 3$, we can reproduce the cubic correlation observed between VHE and synchrotron emission for the case of $n = 3$ and $x > 1$. A similar effect is expected if the VHE radiation is not due to Inverse Compton scattering but due to π^0 decays. A detailed study of hadronic loops and combinations of leptonic and hadronic loops is in preparation.

B. Flaring and permanent neutrino emission states

As discussed above, an enhanced flux of photons can arise from photo-hadronic interactions, leading to the coincident production and emission of neutrinos. In the giant flare, the flux increase was about an order of magnitude for the duration of ~ 60 min. Note, however, that this enhanced flux is only present in the one hour when the source is flaring at very high photon energies. We can make a simple exercise at what point flares can be more significant in neutrino detectors as KM3NeT and IceCube by considering the significance of a detection, $\sigma \sim N_{\text{sig}}/\sqrt{N_{\text{BG}}}$. Here, N_{sig} is the number of signal events, while N_{BG} is the number of background events. The number of signal events in a time interval Δt scales as $N_{\text{sig}} \propto A_\nu \cdot \Delta t$, with A_ν as the intensity of the neutrino signal, which we assume to be variable. The number of background events simply proportional to $N_{\text{BG}} \propto \Delta t$, as the background does not change with time, apart from statistical fluctuations. This results in a significance proportional to $\sigma \propto A_\nu \cdot \sqrt{\Delta t}$.

³we use a Λ CDM cosmology with $(\Omega_m, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)$

If we compare the flaring state to the permanent state, we have $A_{\nu}^{\text{flare}} \approx x \cdot A_{\nu}^{\text{perm}}$, with A_{ν}^{flare} and A_{ν}^{perm} as the intensities of the flaring and permanent neutrino states, connected by an intensity factor of $x \approx 10$. The duration of the flare is $\Delta t^{\text{flare}} \approx 3600$ s, and Δt^{perm} is the observation time for a permanent flux. Now, we can compare the significances of the flaring and the permanent state, σ_{flare} and σ_{perm} :

$$\begin{aligned} \frac{\sigma_{\text{flare}}}{\sigma_{\text{perm}}} &= \frac{A_{\nu}^{\text{flare}}}{A_{\nu}^{\text{perm}}} \cdot \sqrt{\frac{\Delta t^{\text{flare}}}{\Delta t^{\text{perm}}}} = x \cdot \sqrt{\frac{\Delta t^{\text{flare}}}{\Delta t^{\text{perm}}}} \\ &= 10^{-3} \cdot \left(\frac{x}{10}\right) \left(\frac{\Delta t^{\text{flare}}}{3600 \text{ s}}\right)^{1/2} \left(\frac{\Delta t^{\text{perm}}}{1 \text{ yr}}\right)^{-1/2} \end{aligned} \quad (10)$$

This implies that the significance of a flaring state is a factor of 10^{-3} lower compared to the observation of a permanent flux for one year, considering that the flare's intensity is a factor of 10 higher than the permanent emission. This leaves room for different conclusions on whether a flaring state or the permanent neutrino emission would be detected first:

- Consider that Pks2155-304 flares several times a year. If we assume a constant flare activity of $x = 10$, the flaring state needs to be present more than 3% of the time in one year - in that case, the flaring state can be observed before the permanent state. If the flaring rate is less, the permanent flux is likely to be observed earlier.
- Single flares may be difficult to observed given the numbers above, unless there is no permanent emission, i.e. $\Delta t^{\text{flare}} = \Delta t^{\text{perm}}$. The optical depth we present is close to unity, and only a first-order approximation. If this optical depth drops far below unity most of the year, no permanent emission would be present and flaring states are likely to be observed first. In that case, we have $\sigma_{\text{flare}} = x \cdot \sigma_{\text{perm}}$, and selecting flaring states enhances the significance by a factor of x .

V. RESULTS AND CONCLUSIONS

Very high-energy emission is observed from a growing number of blazars. One possible emission scenario for the VHE component is photon production in photo-hadronic interactions. In this paper, we investigate this possibility by estimating the optical depth for proton-photon interactions in the first strong shock of Pks2155-304. Using optical photons, the optical depth in the low-state of Pks2155-304 is close to unity, when assuming interactions with the optical photon field. The observed correlation between optical and VHE wavelength can therefore be interpreted as a result of photo-hadronic interactions - an increased optical flux leads to an enhancement of the proton-photon optical depth and therefore to an increase of the VHE photon and neutrino fluxes.

Flaring states provide the possibility of enhanced neutrino emission, if the VHE radiation is due to π^0 -decays. These flaring states may in some cases

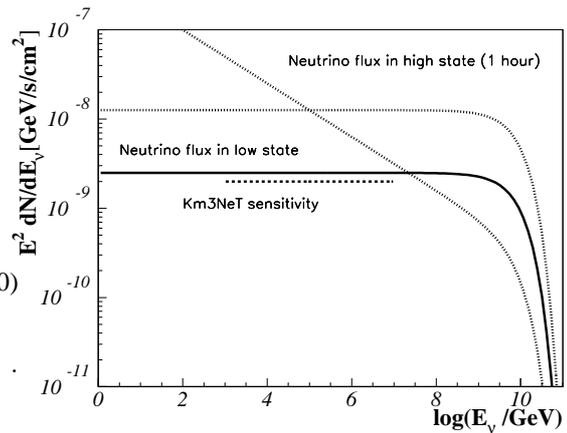


Fig. 1. Neutrino flux from Pks2155-304. The solid line is the predicted average neutrino flux in the low-state as observed in 2008. The dotted lines show the emission level in the high-state of Pks2155-304 as seen by H.E.S.S. As we do not have detailed information of the spectral index, we show two lines, the flat one being an E^{-2} -shaped spectrum, the steep one representing an $E^{-2.3}$ -like behavior.

be the only times of neutrino emission, if the low-state provides too low optical depth for photo-hadronic interactions. While Pks2155-304 provides reasonable optical depth for neutrino production also in the low-state, this may not be the case for other blazars. The stacking of neutrino data during observed flaring states gives the unique opportunity to reduce the background of atmospheric neutrinos in VHE neutrino telescopes like IceCube and KM3NeT: Even a few neutrino events from such flares will be significant.

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