Nuclear Instruments and Methods in Physics Research A 742 (2014) 191–194

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

An exploration of hadronic interactions in blazars using multi-messenger data

C. Tchernin [a,*], J.A. Aguilar [b], A. Neronov [a], T. Montaruli [b]

[a] *Département d'astronomie, Université de Genève, CH-1290 Versoix, Switzerland*
[b] *Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève 4, Switzerland*

ARTICLE INFO

Available online 7 November 2013

Keywords:
Active Galactic Nuclei
Blazars
Cosmic neutrinos
Hadrons

ABSTRACT

High energy photon and neutrino emissions are expected from the interactions of high-energy protons with matter and/or radiation in the blazars environment. In these proceedings, we use the sensitivity of the IceCube neutrino detector estimated for different neutrino spectral indices (derived in Tchernin et al. (2013) [12]) to show that already in its 40-string configuration (IC-40), the sensitivity of the IceCube neutrino telescope is already at the level of constraining the parameter space of purely hadronic scenarios of blazar activity. As a result, using the full detector sensitivity, those constraints should be about a factor of 3 better than what discussed here. Assuming that the γ-ray flux observed by Fermi can be explained with purely hadronic interactions, we estimate the expected neutrino flux from blazars based on the combination of the γ-ray flux observed by Fermi, with the simultaneous IC-40 observations. We consider separately the cases where the proton–proton or proton–γ interactions are dominant. In both cases, we set some constraints on the primary proton spectrum. In the case where pp interactions dominate, the tightest constraints are set for the source 3C 454.3, for which the high energy part of the spectrum is constrained to be harder than E^{-2} and the cut-off energy larger than 10^{18} eV. Alternatively, in the case where the dominant channel is the interaction of the high-energy protons with the soft radiation fields, the magnitude of the constraints depends on the radiation field energy distribution. For the source 3C 273, the most constrained source of our sample for the pγ interaction, the cut-off energy is constrained to be $E_{cut} \gtrsim 10^{18}$ eV for any spectral index and for different soft photon fields, including the radiation from the accretion disk (Big Blue Bump), the broad line region or the synchrotron radiation from the jet.

1. Introduction

Blazars are a special type of radio-loud Active Galactic Nuclei (AGN) emitting jets aligned along the line of sight [13]. Observations of broad-band electromagnetic emission from blazars from the radio to the TeV region show that the jets and/or central engines of blazars and, more generally, radio-loud AGNs, accelerate electrons to extremely high energies. Protons should be accelerated together with electrons, presumably with higher efficiency due to less important energy losses. However, a direct test of the presence of high-energy protons in the source is difficult because of the absence of a clear signature of proton-generated emission in the electromagnetic component of blazar and radio galaxy spectra.

The spectral energy distribution (SED) of blazars is dominated by radiation from non-thermal particle distribution in the jet. It is composed by two broad components. The low energy component is generally attributed to synchrotron radiation from electrons and positrons in the knots moving at relativistic speed in the jet. The high energy component can have different origins depending on the model considered: inverse Compton emission via up-scattering of the synchrotron photons (synchrotron-self Compton model), inverse Compton emission via up-scattering of the external radiation photons (external Compton model), emission from decays of neutral pions produced in proton–proton interactions, (pp) proton–photon interactions $p\gamma$ or proton synchrotron radiation. The maximal attainable energy of γ-ray emission is limited either by the maximal energies of electrons or by the onset of γγ pair creation.

The high-energy electrons responsible for the synchrotron and inverse Compton emission could be either directly accelerated in the jet or have a non-acceleration origin as secondary particles produced by protons and γ-rays interactions. The latter case is the so-called "purely hadronic" model of blazar activity in which all the power of electromagnetic emission from the source is supposed to originate from the interactions of high-energy protons.

Even if the multi-wavelength measurement of SED of sources is becoming more and more precise, it is difficult to distinguish in the high energy region the primary accelerated e^+e^- from the secondary e^+e^- induced by proton-initiated cascades. A direct

---

* Corresponding author.
E-mail address: Celine.Tchernin@unige.ch (C. Tchernin).

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.10.065

verification of the hadronic origin of blazar and radio galaxy activity could be achieved by the observation of high-energy neutrinos from charged pion decays. The energy output of pion production reactions is approximately equally divided between neutrino and electromagnetic/leptonic channels (see e.g. [7,8]).

If the blazars and radio galaxies emitted power comes from high-energy proton interactions, the neutrino flux could be detected by very-high-energy (VHE) neutrino detectors, like the recently completed IceCube telescope at the South Pole. The published upper limits on the neutrino flux from point sources in the Northern hemisphere are derived using one year of about one-half of the detector (IC-40) [1]. The IC-40 limits and sensitivities in the energy region ~10 TeV–10 PeV are already comparable (in terms of the energy flux) with the electromagnetic fluxes of the brightest blazars observed by the Large Area Telescope (LAT) on board of Fermi satellite in the 0.1–100 GeV energy band [3]. The non-detection of neutrino emission from the brightest blazars constrains the parameter space of hadronic models, specifically the proton spectrum and/or of the seed photon field parameters.

In the AGN environment, the main energy loss channels for the high-energy protons are pion production in interactions with the low-energy protons or interactions with radiation fields. An additional possibility is proton synchrotron radiation energy losses. The three channels might, in fact, operate simultaneously in a competing way but in the following we will make the simplifying assumption that one of the channels dominates.

In the following, considering different hadronic models, we will set some constraints on the model parameters characterizing the parent high-energy proton spectrum by comparing the IC-40 sensitivity to the neutrino flux expected from some of the brightest blazars.

2. Hadronic models of blazar activity

2.1. Proton–proton interactions

The relativistic proton can interact with the matter in the source in a very efficient way if the matter density in the source is high enough. In the process of inelastic collisions with low-energy background protons ($p+p\rightarrow\pi^{\{+,-,0\}}+X$), the cross-section of the pion production is almost energy independent, $\sigma_{pp}\sim 4\times10^{-26}\ \text{cm}^2$ [7]. Secondary particles produced in pp interactions are neutrinos, e^+e^- and γ-rays. The cross-section of this process has a threshold given by,[1] $E_{th}=m_p+m_\pi(m_\pi+4m_p)/2m_p\simeq 1.2$ GeV. Therefore most of the accelerated protons could interact in the source and, because of this, the spectra of the produced secondary particles approximately follow the shape of the parent proton spectrum.

If the spectrum of accelerated protons is harder than $dN_p/dE\sim E^{-2}$. The main contribution to the γ-ray emission in the GeV band could come from the e^+e^- pairs produced either in the $\pi^\pm$ decays or in the γγ induced cascade rather than from the π^0 decay. In this work, we will assume that it is the case and we will estimate the overall power of neutrino emission from the overall power of the cascade emission produced during such interactions.

2.2. Proton–γ interactions

The accelerated relativistic protons could also interact with the radiation fields. The target photon field could be the jet synchrotron emission or it can be external to the jet, e.g. originate from the accretion disk or from the jet/accretion disk radiation reprocessed in the Broad Line Region (BLR) or from the radiation of the dusty torus [11]. The minimal required proton energy for the pion production by interaction with the radiation fields is larger than for pp interaction: $E_{th}=(2m_p m_\pi+m_\pi^2)/(4\varepsilon_{ph})\simeq 7\times10^{16}$ $[(\varepsilon_{ph})/(1\ \text{eV})]^{-1}$, where m_p, m_π are the masses of proton and pion /gamma respectively and ε_{ph} is the energy of the target photons. Because of this energy threshold, only the highest energy protons could efficiently interact with the soft-photon fields.

In the pγ models, the characteristic feature of the neutrino spectrum is that, independently of the primary proton spectrum shape, the neutrino spectrum extends from the threshold energy up to the maximal energies of the protons, $E_{max,p}$. The condition for non-null efficiency in the pγ models is therefore that $E_{max,p}>E_{th}$.

2.3. Proton/muon/pion synchrotron models

Proton acceleration to high energies requires strong electromagnetic fields. At the same time, the presence of strong magnetic fields leads to inevitable synchrotron energy losses, which could efficiently remove energy from the high-energy protons and result in γ-ray emission. This opens the possibility that the observed γ-ray emission from the blazars might be the synchrotron radiation of the accelerated protons Aharonian [4].

If the magnetic field strength in the source is larger than several tens of Gauss, the synchrotron emission dominates over the other interaction channels. Then, since muons, and, possibly, pions would lose energy via synchrotron radiation before decaying, the efficiency of neutrino production will be reduced with respect to the case of pp and pγ models. Consequently, contrary to the pp and pγ scenarios, the flux of neutrinos emitted by the source is in this case not directly related to its γ-ray flux.

In this study, we only consider pp and pγ scenarios. But in the case of non-negligible synchrotron losses, the constraints reported in this study would be largely relaxed.

3. Selection of blazars using Fermi data

For this study we analyzed simultaneous observations of the brightest blazars in the 0.1–100 GeV γ-ray band by the Large Area Telescope (LAT) on board of Fermi satellite [6] in order to derive the expected level of neutrino flux: from August 4, 2008 to May 9, 2009.[2]

Table 1 shows the list of northern sources with an average (over 2 years covered by the second Fermi catalog [2]) flux greater than $>10^{-10}\ \text{erg/cm}^2\ \text{s}$.

4. Constraints on hadronic interaction models

Non-detection of the sources in one-year exposure by IC-40 implies non-trivial bounds on the parameters of the high-energy proton spectra in the context of purely hadronic models of blazar activity. In what follows we discuss the constraints on the

---

[1] We assume the unit system with $c=1$.

[2] A preselection of blazars from the two-year Fermi catalog [2] was done by requiring an average flux (over the 0.1–100 GeV) greater than $10^{-10}\ \text{erg/cm}^2\ \text{s}$. For each selected blazar, we performed the standard Fermi data analysis using the Fermi Science Tools[3] version v9r23p1. We filtered the data using the `gtselect` tool to select only events which are most likely γ-rays (`evclass=3`). All the sources considered in our analysis are at high Galactic latitudes $|b|>10^\circ$ and therefore the diffuse sky background around the source positions is not strongly variable on the degree scales. Taking this into account, we used the "aperture photometry" method to calculate the lightcurves and spectra of the sources. We have verified that the aperture photometry method of spectral extraction agrees with the results of the likelihood analysis (an alternative spectral extraction method used for the LAT data analysis). The exposure is calculated using the `gtexposure` tool also part of the Fermi framework.

[3] http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/