Self-consistent neutrino and UHE cosmic ray spectra from Mrk 421

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Abstract

We examine the neutrino and cosmic ray spectra resulting from two models of fitting the spectral energy distribution (SED) of the blazar Mrk 421 using a self-consistent leptohadronic code. The γ-ray emission is attributed to either synchrotron radiation of ultra-high energy protons (LHs model) or to synchrotron radiation from electrons that result from photopion interactions of lower energy protons (LHR model). Although both models succeed in fitting satisfactorily the SED, the parameter values that they use result in significantly different neutrino and cosmic-ray spectra. For the LHR model, which requires high proton energy density, we find that the neutrino spectrum peaks at an energy $E_{\nu,\text{peak}} = 3.3$ PeV which falls well within the energy range of recent neutrino observations. While at the same time its peak flux is just under the sensitivity limit of IC-40 observations, it cannot produce ultra-high energy cosmic rays. In the LHs model, on the other hand, neutrinos are far from being detectable because of their low flux and peak energy at $E_{\nu,\text{peak}} \simeq 100$ PeV. However, the propagation of protons produced by the decay of escaping neutrons results in an ultra-high energy cosmic ray flux close to that observed by Pierre Augere, HiRes and Telescope Array at energies $E_p \approx 30$ EeV.

Keywords:
Ultrahigh energy cosmic rays, Neutrinos, Sources of extraterrestrial neutrinos, Radiation mechanisms: non-thermal, Gamma ray emission, Photo hadronic interactions, Active Galactic Nuclei

1. Introduction

Fermi and ground-based TeV observations have convincingly proved that blazars, a class of Active Galactic Nuclei having their jets pointed towards us, can be considered as very efficient particle accelerators. It is possible then that an active region in a blazar jet, such as a standing shockwave, can accelerate both protons and electrons to high energies. In such a case electron synchrotron radiation is responsible for the blazar emission from the radio up to UV/X-ray regime while the high energy (GeV-TeV) emission is attributed to processes induced by hadrons which include proton synchrotron radiation [1] [2] and pion-related cascades [3], producing thus the characteristic double hump blazar Spectral Energy Distribution (SED) in a $\nu F_{\nu}$ vs. $\nu$ diagram.

It is well known that the ultimate proof for the existence of high energy protons in blazar jets can only come from the detection of high energy neutrinos. An accurate modelling of such neutrino spectra is vital for the interpretation of observations by neutrino telescopes, especially in the context of the recent observation of neutrino showers in the PeV energy range by IceCube [4]. A common approach is to suppose a generic proton distribution at the source and from that to obtain a neutrino spectrum, which can then be integrated over redshift to give us the total flux at Earth (e.g., [5] [6], or in the context of PeV neutrinos, [7]).

In the present paper we will follow a different approach. We will use a recently developed numerical code that treats the radiative transfer problem in a region where both electrons and protons are accelerated. This will allow us to calculate the proton distribution at source simultaneously with the radiated photon spectrum. We will consequently seek successful fits to the SED of the well monitored BL Lac object Mrk 421. As the numerical code calculates not only the photon spectra but also the emergent neutron and neutrino ones, the obtained SED fits will automatically give the production spectra of these two other species expected from the particular source.

In Section 2 we briefly present the numerical code and the relevant free parameters. In Section 3 we present the results for two applications of the model, and we conclude in Section 4 with a summary and some discussion.

2. The model

In this section we will present the principles of the adopted numerical code. While details can be found in [8], for the sake of completeness we summarise here its basic points. We have assumed that protons and electrons, accelerated up to high

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energies, are injected uniformly with a constant rate inside a spherical volume of radius $R$ containing a tangled magnetic field of strength $B$. Both species lose energy by various physical processes: Protons lose energy by synchrotron radiation, photopair and photopion production. All photopion interactions, including the decay of produced pions and muons, have been modelled using the results of the SOPHIA event generator \cite{9}, while photopair interactions are modelled using the Monte Carlo results of \cite{10}. The stable secondary products of these processes include electron/positron pairs (which will be hereafter collectively referred to as electrons), photons, neutrons and neutrinos. Muons, which are unstable secondary products, are allowed to lose energy through synchrotron radiation before their decay. Electrons (primary and secondary) lose energy by synchrotron radiation and inverse Compton scattering, while gamma-rays can be absorbed on the softer photons, produced mainly by electron synchrotron radiation, creating more electron-positron pairs. Neutrons, not being confined by the magnetic fields in the source, can either escape or interact with the photons before decaying back to protons. Finally neutrinos constitute the most uncomplicated component as they escape from the source essentially with their production spectrum.

In order to follow the evolution of this non-linear (see \cite{11}) system we use the kinetic equation approach; thus we write five time-dependent equations, for each stable species, namely for protons, electrons, photons, neutrons and neutrinos. The various rates are written in such a way as to ensure self-consistency, i.e. the amount of energy lost by one species in a particular process is equal to that emitted (or injected) by another. That way one can keep the logistics of the system in the sense that at each instant the amount of energy entering the source through the injection of protons and primary electrons should equal the amount of energy escaping from it in the form of photons, neutrons and neutrinos (in addition to the energy carried away due to electron and proton escape from the source). We have not included an additional equation describing the evolution of pions because their decay rate is far higher than its synchrotron energy loss rate, so the latter can be safely neglected. As this condition does not apply for muons we have made an adjustment to the code described in \cite{8}. For each muon energy, we calculate the energy lost to synchrotron radiation before it decays. Then the secondaries corresponding to the reduced muon energy, whose yields have also been computed by the SOPHIA event generator \cite{9}, are essentially produced instantaneously. Moreover, these products along with muon synchrotron photons are added to their respective kinetic equations without the need for a separate equation for muons.

The above approach has various advantages: since it uses a particle injection rate, one can calculate the efficiency of the model – note that the most usual approach of using a particle distribution function in order to calculate the resulting spectra cannot give such estimates. Furthermore, it can calculate in an exact way – under the assumption of a spherical geometry – the photon, neutron and neutrino transport and thus compare directly their respective fluxes. Finally it can treat both stationary and time-dependent cases, thus providing a tool for studying time variability in the context of a leptohadronic model – see \cite{12}.

Our free parameters, as measured in the rest frame of the emitting region, are limited to the following:

1. the injected luminosities of protons and electrons, which are expressed in terms of compactnesses:
   \begin{equation}
   L_{\text{inj}}^i = \frac{L_{\text{e}T}}{4\pi Rm_c c^3},
   \end{equation}
   where $i$ denotes protons or electrons and $\sigma_T$ is the Thomson cross section;
2. the upper Lorentz factors of the injected protons and electrons, $\gamma_{p,\text{max}}$ and $\gamma_{e,\text{max}}$ respectively;
3. the power law indices $p_p$ and $p_e$ of injected protons and electrons, respectively;
4. the radius $R$ of the region;
5. its magnetic field, $B$;
6. its Doppler factor, $\delta$; and
7. the escape time for both particles, which is assumed to be the same ($t_{p,\text{esc}} = t_{e,\text{esc}}$).

Finally, the lower Lorentz factors are assumed to be $\gamma_{p,\text{min}} = \gamma_{e,\text{min}} = 1$.

As in \cite{12}, we have adopted a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70\, \text{km s}^{-1}\, \text{Mpc}^{-1}$, where the redshift of Mrk 421 $z = 0.031$ corresponds to a luminosity distance $D_L = 0.135\, \text{Gpc}$.

3. Results

Being one of the closest blazars to Earth, Mrk 421 has been the target of multiple multiwavelength (MW) campaigns over the years. Observations by \cite{13} in 2001 produced excellent sets of time-dependent data both at the X-ray (RXTE) and TeV (Whipple and HEGRA) regimes during a six-day period. In \cite{12} we used a variation of our model to fit Mrk 421 in its preflare state of March 22nd/23rd 2001 and then applied time-dependent fluctuations of the injection compactnesses or of the maximum energies of injected protons to study the interplay between variations of X-ray and $\gamma$-ray fluxes. We corrected also our model predicted $\gamma$-ray spectra for photon-photon absorption on the extragalactic background light (EBL) by using the model of \cite{14}. However, the effects of EBL absorption are negligible due to the proximity of the source to Earth. Our fitting is based only on X-ray and TeV observations since no GeV data were available during the 2001 campaign. For comparison reasons, we included in our model SEDs the Fermi data during the period of the IceCube 40-string configuration (IC-40) \cite{15}. Inclusion of the additional spectral information would only slightly alter our parameter values. Here we have focused on the steady state emission of Mrk 421 in order to examine the resulting neutrino and neutron distributions in relation to the observed photon spectra. Instead of using the conventional IC-40 upper limits \cite{16}, which are derived for soft neutrino spectra emitted by a generic source, we adopted those given by \cite{17} that are calculated specifically for Mrk 421 and for different power-law neutrino spectra.
with certain acceleration models (e.g. [19]) GeV-TeV emission is different between the two models. Fitting with a representative mass in a narrow range of parameter values. Within this range, we found, interestingly enough, two sets of very different proton injection parameters which give good fits to the data. In both cases, optical and X-rays are fitted by the synchrotron radiation of electron/positron pairs that result both from charged pion decay and from the absorption of $\gamma$-rays from neutral pion decay. The combination of a low magnetic field with a high proton injection compactness results in suppressed proton synchrotron emission and prominent photopair and photopion components. Thus the SED does not have the usual double hump appearance as synchrotron photons from the photopair secondaries produce a distinctive broad hump at MeV energies.

In the LHs model, TeV $\gamma$-rays are produced by proton synchrotron radiation. The high magnetic field coupled with a low proton injection compactness results in a suppressed photopair and photopion component and two well defined peaks, both from synchrotron radiation of electrons at low energies and from protons at higher.

### 3.2. Neutrino emission

In Figs. 1 and 2 the neutrino spectra (light blue lines) obtained in both models are shown along with the photon spectra. The neutrino spectral parameters, compared to those of other particle types, are summarized in Table 2. Note that the luminosities are given in the comoving frame. Although the neutrino flux contains neutrinos of different flavours with an approximate ratio $F_{\nu_e} : F_{\nu_x} : F_{\nu_\tau} = 2 : 1 : 0$, by the time they reach Earth their ratio will have changed to $F_{\nu_e} : F_{\nu_x} : F_{\nu_\tau} = 1 : 1 : 1$

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**Table 1: Initial parameters for the two fits.**

| Parameter | model LHs | model LHs |
|-----------|-----------|-----------|
| $\gamma_{p,\text{max}}$ | $3.2 \times 10^9$ | $6.3 \times 10^9$ |
| $\gamma_{e,\text{max}}$ | $8 \times 10^4$ | $4 \times 10^4$ |
| $p_p$ | 1.3 | 1.5 |
| $p_e$ | 1.2 | 1.2 |
| $\ell_p$ | $2 \times 10^{-3}$ | $1.6 \times 10^{-7}$ |
| $\ell_e$ | $3.2 \times 10^{-5}$ | $10^{-4}$ |
| $R$ (cm) | $3.2 \times 10^{15}$ | $3.2 \times 10^{13}$ |
| $B$ (G) | 5 | 50 |
| $\delta$ | 26.5 | 21.5 |

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**Figure 1:** Spectra of photons (black line) fitting the March 22nd/23rd 2001 observation of Mrk 421 (purple points), neutrinos of all flavours (light blue line) and muon neutrinos (thick blue line) arriving at Earth, after taking into account neutrino oscillations according to the photopion model LHs. Fermi observations [15] (green points) are not simultaneous with the rest of the data. The 40-String IceCube limit for muon neutrinos [12] is plotted with an orange line.

We note here that for the SED modelling of Mrk 421 we did not attempt a best $\chi^2$ fit but instead we followed the approach of [18], where they considered families of acceptable fits to the data. This allows us to use a narrow range of parameter values. Within this range, we found, interestingly enough, two sets of very different proton injection parameters which give good fits to the data. In both cases, optical and X-rays are fitted by the primary injected leptonic component, while the origin of the GeV-TeV emission is different between the two models. Fitting of the optical data requires in both cases electron distributions that are flat, still with indices ($p_e = 1.2$) that are compatible with certain acceleration models (e.g. [19]). In what follows, we will discuss the resulting photon, neutrino and ultra-high energy cosmic ray (UHECR) spectra obtained in both cases.

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2In the above fits we have used $\gamma_{e,\text{min}} = 1$. If we were to relax this constraint and allow higher values of the lower energy cutoff we could obtain acceptable fits with steeper power-law distributions, which would be easier to reconcile with more acceleration models.

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3In general we find that, for most relevant fitting parameters, protons lose approximately the same amount of energy through photopair and photopion interactions, therefore those two processes have the same significance for the injection of secondaries.
due to oscillations [20]. Since we are comparing our spectra to the IceCube sensitivity for muon neutrinos (orange line) we have to scale down our results by a factor of 3 – see thick blue lines in Figs. [1] and [2]. The IC-40 limit in our figures is derived for arbitrary power-law neutrino spectra. Thus, for a given slope of a power-law neutrino spectrum the tangent to the envelope curve having the same slope gives the actual upper limit.

The low efficiency of photodihadronic interactions in the LHS model results in a neutrino flux that is by many orders of magnitude lower than the IC-40 upper limit and about a factor of 3 less than the TeV $\gamma$-ray flux. The peak of the neutrino flux occurs at energies of 100 PeV due to the high values of the magnetic field and the maximum Lorentz factor of protons.

On the other hand, the LH$\pi$ model produces a substantial neutrino flux that is of the same order as the TeV $\gamma$-rays. We can then see that the expected neutrino flux is just under the sensitivity of the IC-40 detector, and should be producing observable neutrinos for subsequent layouts with 79 or 86 strings. The peak neutrino flux is observed at energies around $E_{\nu,\text{peak}} = 3.3\text{PeV} \nu_f$. This corresponds to an energy about 30 times lower than the maximum proton energy in the $\nu F_\nu$ vs. $\nu$ diagram. At lower energies it follows an approximate power law with index $p_\nu$, which is harder than the power law of the initial protons by a factor of ~1, in accordance with the approximate relation $p_\nu \approx (p_p - 0.5)/2.5$ from [3]. Neutrinos from neutron decay peak at an energy two orders of magnitude lower than those from meson decay and their luminosity is similarly lower. In this case their contribution is noticeable as a small peak to the left of the main neutrino spectrum peak in Fig. [1].

Table 2: Neutrino parameters compared to the respective ones of the parent proton distribution. The values of the proton ($\nu_\pi$) and magnetic field ($\nu_B$) energy densities refer to steady state; the luminosities of primary electrons, photons and neutrons are also included as is the total observed luminosity of the jet.

| Parameter         | model LH$\pi$ | model LH$\pi$ |
|-------------------|---------------|---------------|
| $\gamma_{p,\text{max}}$ | $3.2 \times 10^6$ | $6.3 \times 10^7$ |
| $E_{\nu,\text{peak}}$ | $1.3 \times 10^5$ | $1.6 \times 10^8$ |
| $p_\nu$           | 1.3           | 1.5           |
| $p_\nu$           | 0.3           | 0.3           |
| $L_p (\text{erg s}^{-1})$ | $5.7 \times 10^{33}$ | $4.5 \times 10^{31}$ |
| $L_{e\nu} (\text{erg s}^{-1})$ | $4.6 \times 10^{40}$ | $1.2 \times 10^{41}$ |
| $L_{\nu} (\text{erg s}^{-1})$ | $6.9 \times 10^{30}$ | $1.3 \times 10^{41}$ |
| $L_{\gamma} (\text{erg s}^{-1})$ | $7.9 \times 10^{39}$ | $7.4 \times 10^{38}$ |
| $L_\nu (\text{erg s}^{-1})$ | $3.8 \times 10^{40}$ | $2.6 \times 10^{39}$ |
| $\nu_0 (\text{erg cm}^{-2})$ | $1.6 \times 10^4$ | $9.7 \times 10^{-2}$ |
| $\nu_\nu (\text{erg cm}^{-2})$ | 100 | 100 |
| $P_{\text{obs}} (\text{erg s}^{-1})$ | $1.1 \times 10^{48}$ | $4.2 \times 10^{46}$ |

3.3. UHECR emission

Neutrons resulting from photopion interactions are an effective means of facilitating proton escape from the system, as they are unaffected by its magnetic field and their decay time is high enough to allow them to escape freely before reverting to protons [21,22,23,24]. A further advantage is that they are unaffected by adiabatic energy losses that the protons may sustain in the system as it expands [5]. Those effects make them excellent originators of UHECR. In Fig. [3] we show the ultra-high energy neutrino spectrum having first decayed into protons, as obtained by the LH$\pi$ (red solid line) and the LHS (black dashed line) models.

The plotted spectrum of the LH$\pi$ model is just an upper limit of what it would appear at Earth, in the absence of cosmic-ray diffusion. We have not taken that into account because treating it at energies $< 10^{17}$ eV would lie outside the scope of the present paper that focuses on UHECR. At any rate, our values, even as an upper limit, are well below the observed CR flux at such energies.

In the LHS model, however, the higher value of the maximum proton Lorentz factor used in the SED fitting makes the discussion about UHECR emission more relevant – see black dashed line in Fig [3]. In this case, the propagation of UHE protons in a uniform intergalactic pG magnetic field (transverse to the direction of propagation) and their energy losses from interactions with the cosmic microwave and infrared and optical (IRO) backgrounds were modelled using CRPropa 2.0 [25]. In particular, the mean free paths of UHE protons for pair- and pion-production processes on the IRO backgrounds are modelled using the best-fit model by [14]. Since at this energy range those losses are the dominant factor in reshaping the proton spectrum and diffusion effects are minimal, we have restricted ourselves to one-dimensional (1D) simulations. The resulting spectra in Fig. [3] (blue crosses) are compared to observations from Auger [26] (open triangles), HiRes-I [27] (open squares) and Telescope Array [28] (x-symbols). At energies 30 – 60 EeV the expected cosmic rays are just under the present limits; we remind that our results are obtained by fitting Mrk 421 in a low state. During a flaring state the produced UHECR flux will be even higher.

It could explain some of the discrepancy between the Auger and HiRes-I/Telescope Array data at that energy range, since Mrk 421 is in the northern sky and, thus, invisible to Auger. Interestingly enough, the same applies for every other high-frequency-peaked BL Lac within a distance of $z = 0.05$ [29]. It is more difficult to assess the contribution of escaping protons to the UHECR spectrum. The proton flux is two orders of magnitude higher than the neutron one but, unlike neutrons, protons are subjected to adiabatic losses after escaping from the active region. In particular, if the emitting region lies within an expanding jet, the escaping protons will be susceptible to adiabatic energy losses and may end up carrying a negligible fraction of the UHECR flux, while the main contribution comes from protons produced by neutron decay. A study
of the escaping proton contribution lies outside the scope of the present paper since it requires assumptions on the specific geometry of the jet.

An interesting question that might be addressed is the level of the line-of-sight neutrino/γ-ray flux resulting from the UHE proton propagation. Figure 4 shows the secondary γ-ray (blue crosses) and neutrino spectra (green crosses) produced by interactions of UHE protons with the CMB and IRO backgrounds, derived for the LHs model using CRPropa 2.0; our model spectra coming directly from the source (blue and green solid lines) are overplotted for comparison reasons. We note that in 1D propagation simulations the strength of the uniform intergalactic magnetic field affects only the synchrotron emission of the secondaries produced during the UHECR propagation while it does not cause any deflections; in this sense, it can be considered as an upper limit. Even in the extreme case of an intergalactic magnetic field of 1 μG strength, the secondary γ-ray and neutrino emission was found to be at least one order of magnitude below the LHs source emission. The assumption of a structured intergalactic magnetic field would result in the deflection of UHECR by an angle of a few degrees (see e.g. [33]) with respect to our line-of-sight and, therefore, lead to an even lower flux emitted by the charged secondary particles produced during the propagation.

4. Summary/Discussion

In the present paper we have calculated the detailed neutrino and neutron spectral flux emerging from the BL Lac object Mrk 421 under the assumption of a one-zone leptohadronic model. Even if the assumed geometry of the source is simple enough, we have applied a sophisticated method to calculate in self-consistent and time-dependent way the photopion and photopion interactions. For this we used the numerical code presented in [8] and made fits to the MW spectrum of this source as obtained in 2001 using contemporaneous optical, X-ray and TeV γ-ray data [13]. Using then the so-obtained fitting parameters allowed us to calculate the expected neutron and neutrino fluxes. Consequently we have followed the propagation of protons, which result from the escaping neutron decay, and thus calculated the expected UHECR contribution of Mrk 421 at Earth.

We found that two sets of very different parameters produce good fits to the SED of the source. In the first case, γ-rays are produced from synchrotron radiation of secondaries resulting from photopion interactions, therefore they are pion-induced (the LHr model). In the other case, the γ-rays originate from proton synchrotron radiation (the LHs model).

Proton acceleration at ultra-high energies, i.e. \( E_{p,\text{max}} = 1.4 \times 10^{20} \text{ eV} \), is a typical feature of the LHs model (see also [1]), which agrees well with the requirement for UHECR accelerators. Although it is magnetically dominated it is a much more economic model than LHr in terms of total jet luminosity – see Table 2. Propagation of the protons produced from the escaping neutron decay results in a UHECR flux at Earth that is very close to the measurements of current experiments at energies around 30 EeV. However, due to the fact that our UHECR spectrum is peaked at high energies, its overall shape is very different from the observed one at energies below 30 EeV – see Fig. [3]. Even if one assumes that all other Northern Hemisphere nearby BL Lac objects produce the same spectral shape of UHECRs as Mrk 421 and normalize their cosmic-ray output to their photon luminosity, their contribution to the total UHECR flux will not be significant because of the combina-
tion of their low luminosities and of the cosmic-ray propagation through larger distances; we remind that among these sources, Mrk 421 is not only the closest blazar but also the most luminous one. Furthermore, the LHs model produces a low neutrino flux, since photohadronic processes are suppressed to a level that is many orders of magnitude below the IceCube sensitivity threshold – see Fig. 3. While it is possible to fit the SED with steeper proton injection spectra, we found that these cases cannot alter significantly our conclusions regarding UHECR and neutrino fluxes, as long as \( p_0 < 2.5 \).

The LHr model, on the other hand, requires a large, but not unacceptable, jet power which is heavily particle dominated – see Table 2. Good fits to the SED of the source are obtained assuming that the protons are accelerated up to \( E_p \approx 30 \text{ PeV} \), therefore they cannot contribute to the UHECR flux. However, the produced neutrino flux is tantalizingly close to the IC-40 sensitivity limit for Mrk 421 [17] and peaks within the energy range where the first PeV neutrino detection from the IceCube collaboration was reported [4]. A shortcoming of the LHr model is its low efficiency. If we define the total efficiency \( \xi \) as the ratio of the sum of escaping luminosities in photons, neutrons and neutrinos over the sum of the injected luminosities, then we find \( \xi \approx 2 \times 10^{-5} \). That could be partially alleviated if we assume that the protons are injected at a lower luminosity but gradually pile up inside the source due to a larger escape time compared to the crossing time of the source.

The present work is focused on the high-peaked blazar Mrk 421. Thus, the distribution of ultra-high energy protons that we use in order to derive the neutrino and UHECR spectra is specifically determined by fitting its contemporaneous SED. Generally, we find that homogeneous leptohadronic one-zone models can give very good fits to the MW observations of Mrk 421. A question that arises then is whether such results can be safely generalized and, if so, to what extent. For example, in our calculations we used only intrinsically produced photons as targets for the photohadronic interactions; this can be safely assumed in the case of high-peaked BL Lacs but by no means can be generalized. Thus, if we were to model another source, e.g. a flat spectrum radio quasar which is generally more luminous than a typical BL Lac, and has a high abundance of external photons (e.g. from the Broad Line Region), we would require very different parameters from the ones derived here.

An approach for calculating diffuse neutrino and UHECR fluxes would have then been to calculate simultaneous MW fits to the blazar sequence [34] by means of a leptohadronic model whenever possible. Using these as templates one could, in principle, calculate the neutrino and neutron flux for each class of objects and then integrate over redshift. We plan to perform this type of calculation in a forthcoming paper.

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