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Development of hadronic emission processes in the open-source python package AGNpy

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AGNpy is an open-source python package designed to model the radiative processes at work in the jets of active galactic nuclei (AGN) and blazars, whose high energy emission can arise due to both leptonic and hadronic processes. The former assumes the emission to be dominated by electrons and positrons, while the latter considers a significant contribution by protons. A first version of the package allowed a fully leptonic interpretation of the sources spectral energy distribution (SED). However, the evidence for multi-messenger photon and neutrino emission from the blazar TXS 0506+056, in 2017, suggested blazars as potential neutrino – and thus cosmic-ray – sources giving relevance to the role of protons in blazar jets. In this contribution we present the implementation of the first hadronic processes in AGNpy: synchrotron emission from accelerated protons and radiation of secondaries from photo-meson interactions, in particular. The user is now able to model the sources SED also by means of hadronic and lepto-hadronic processes and to estimate the spectra of the produced muons and neutrinos. We show the software validation through comparison with other codes and few examples of application. These additions make agnpy the first open-source software allowing also a lepto-hadronic interpretation of AGNs emission. The development of hadronic processes in an open-source package opens the modelling effort to a larger community of astrophysicists and ensures the reproducibility and validation of results, becoming essential with the amount of open access data that will be provided by the next generation high-energy observatories.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1524

1. Introduction

Active Galactic Nuclei (AGN) are bright objects powered by accreting supermassive black holes and $\sim 10\%$ of them host jets of relativistic particles. The blazar class shows the jet pointing in the direction of the observer, which results in a Doppler boosting of the emission, making them the most luminous subclass of AGNs. Their Spectral Energy Distribution (SED) covers the whole electromagnetic spectrum and can be interpreted in terms of leptonic or hadronic emission mechanisms. The former assume the jet emission to be dominated by accelerated electrons and positrons through synchrotron or inverse Compton radiation. In this scenario, protons are likely to be present in the jet but not accelerated to sufficiently high energies to significantly contribute to the emission. The latter consider a jet dominated by protons, where the main emission processes are synchrotron emission from relativistic protons and photo-hadronic interactions, resulting in particle cascades. A fundamental difference between these two approaches is that only hadronic models involve the production of neutrinos. Thus, the detection of high-energy neutrinos would pinpoint to the acceleration sites of protons and hence cosmic-rays, whose progenitors are still unknown.

The interest in blazars as potential neutrino emitters grew in 2017, when a high-energy neutrino detected by IceCube was found in spatial and temporal coincidence with the flaring blazar TXS 0506+056 [1]. Several models were developed to describe such multi-messenger observation, whose hadronic contribution was potentially explained as coming from photo-meson interactions (see e. g. [2]), one of the main processes when taking into account jetted AGNs. However, so far, all the developed model softwares including hadronic emission processes are private and only accessible to small groups of developers (see e. g. [3–6]), thus creating issues related to the validation and reproducibility of their results.

In this contribution we present an extension of the open-source python package `agnpy` [7], initially accounting for leptonic emission processes only and now taking into account hadronic ones too. In particular, the two processes presented here are the synchrotron radiation by relativistic protons and the radiation of secondaries from photo-hadronic interactions. The aim of this work is the creation of the first open-source software package allowing also for an hadronic and lepto-hadronic interpretation of the emission of AGNs. Having an open-source software for such purposes, available to the whole astrophysical community, will be essential in the coming years. Indeed, the new generation high-energy observatories, like for example the Cherenkov Telescope Array, will provide a great quantity of open-access data, for which astrophyisicists have already started to develop standardized data formats and public analysis tools. Given the amount of data they will facilitate, it will be necessary to extend the modeling effort to the largest possible number of astrophysicists and here resides the importance of having available open-source softwares.

2. The open-source python package `agnpy`

`agnpy` is a open-source software specifically designed for modeling the broad band emission of jetted AGNs [7]. It is written in python programming language and built on the `NumPy`, `astropy`, and `SciPy` packages. Moreover, it is interfaceable with the fitting routines of `Gammapy` and `Sherpa` data-analysis tools in order to let the user able to perform a fit of a specific model to real data. The package contains modules to initialize a spherical emission region in the jet, responsible for the non-thermal radiative output and to define thermal emitters acting as targets for specific processes like the External Compton scattering. To date, the code only contains the relevant leptonic processes at work in jetted AGNs emission, like synchrotron radiation, synchrotron self Compton or external Compton, without contemplating the possibility of hadronic emission from the considered sources. Being this a potential limitation of the code and given the mentioned photon-neutrino coincidence in 2017 [1], we started the development of hadronic processes in the package, which are briefly presented in the following sections.

3. Implementation of hadronic radiative processes

3.1 Synchrotron emission from relativistic protons

Sychrotron radiation is produced by charged particles moving in a magnetic field. In the case of AGNs, and blazars in particular, synchrotron radiation from relativistic electrons in the jet is known to be the process responsible for the low-energy peak in the SED. However, in presence of high magnetic fields or large proton densities, also the synchrotron radiation from accelerated protons becomes relevant and, in some cases, can well describe the high-energy peak of the SED.

The class `agnpy.synchrotron.proton_synchrotron` allows the computation of the proton synchrotron spectrum assuming the particles to be immersed in a random magnetic field. The parametrization follows [8, 9] as for the electron case. The synchrotron flux emitted by an emission region moving at relativistic speed in a magnetic field B is given by

$$\hat{f}^{syn}_{\hat{\epsilon}} = \frac{\delta_D^4}{4\pi d_L^2}\epsilon' \frac{\sqrt{3}e^3 B}{h}\int_1^\infty \mathrm{d}\gamma'\, N_p(\gamma')R(x), \tag{1}$$

where e is the electron charge, d_L is the luminosity distance of the source, δ_D is the Doppler factor of the emission region, ϵ' is the energy of the emitted photons, $N_p(\gamma')$ is the proton distribution, $R(x)$ is the pitch-angle-averaged synchrotron spectral power of a single electron and $x = \frac{4\pi\epsilon' m_p^2 c^3}{3eBh\gamma'^2}$ [9]. For $R(x)$ the analytical approximation from [10] is used, providing an accuracy better than 0.2%.

In order to validate the implementation, we compared the results with the ones obtained with the private code LeHa-Paris [6]. It is a well-established tool providing the steady-state emission of photons and neutrinos generated in various leptonic and hadronic emission processes and considering a spherical emission region as `agnpy`. For the validation we considered a spherical blob with an energy distribution of relativistic protons following an exponential cut-off broken power-law. Fig. 1 shows the comparison between the spectrum obtained with `agnpy` and LeHa, while Table 1 reports the parameters used. In the bottom panel of Fig. 1, the deviation between the two results is quantified through the quantity $\frac{\nu F_{\nu,agnpy}}{\nu F_{\nu,LeHa}} - 1$ and it results to be less than 5%, stating a good agreement between `agnpy` and the reference.

3.2 Photo-meson interactions

One of the main hadronic processes considered in the jet emission of AGNs and blazars is the so called photo-meson interaction, namely the interaction between a high-energy proton with a low-energy photon, typically coming from the environment. In blazars jets the photon fields

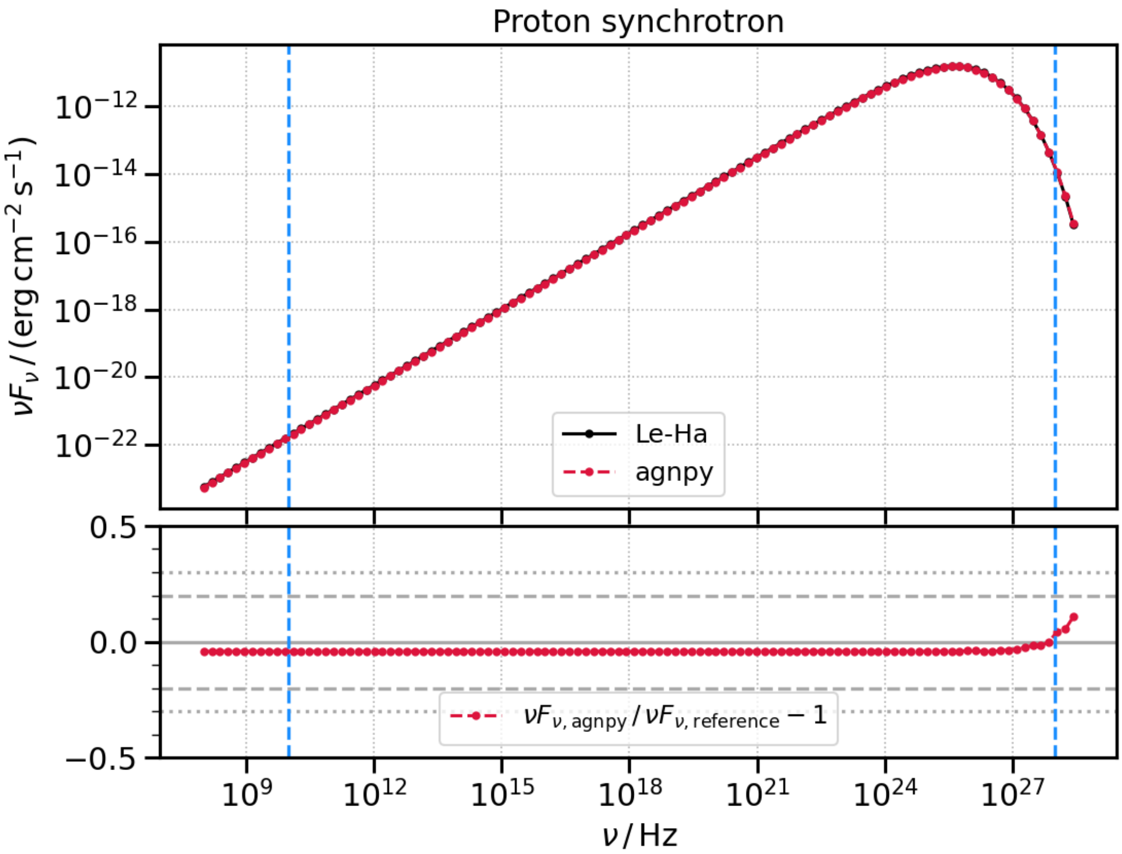

Figure 1: Comparison of the proton synchrotron radiation computed with `agnpy` (red) and LeHa-Paris (black). The bottom panel shows the deviation of `agnpy` from the reference.

Table 1: Model parameters for proton synchrotron model shown in Fig. 1. Parameters related to the emission region are reported on the left, while the ones related to the proton distribution are reported on the right.

Parameter	value
z	0.044
δ	30
B [G]	62.89
R [cm]	9.06×10^{14}

Parameter	value
$\gamma'_{p,min}$	1
$\gamma'_{p,break}$	3.64×10^{9}
$\gamma'_{p,cut}$	3.64×10^{9}
$\gamma'_{p,Max}$	1×10^{20}
$\alpha_{p,1}$	1.5
$\alpha_{p,2}$	2.5
k_p [cm^{-3}]	3.51×10^{-18}

usually considered are the same taken into account in the external Compton process, for example the radiation from the broad line region, the disk or the torus. This process gives origin to neutral and charged pions which decay into $\gamma-$rays, electrons, positrons and *neutrinos*.

The class `agnpy.photo_meson` implements the analytical parametrization of this process from [11]. In this work the spectrum of the secondary particles created through the photo-meson process are obtained by running numerical simulations based on the Monte Carlo code SOPHIA.

The results were then approximated by the authors with analytical fitting functions. According to [11], the spectrum of each produced particle can be presented in the form

$$\frac{dN}{dE} = \int_{\eta_0}^{\infty} H(\eta, E)\, d\eta, \tag{2}$$

where η_0 characterizes the threshold of the interaction and it is given by $\eta_0 \equiv 2\frac{m_\pi}{m_p} + \frac{m_\pi^2}{m_p^2} \simeq 0.313$, while

$$H(\eta, E) = \int_{E}^{\infty} \frac{dE_p}{E_p^2}\, f_p(E_p)\, f_{ph}\left(\frac{\eta\, m_p^2 c^4}{4E_p}\right) \Phi_i\left(\eta, \frac{E}{E_p}\right). \tag{3}$$

Here, m_p is the proton mass, c is the speed of light, E_p is the protons energy, $f_p(E_p)$ is the energy distribution of protons, η is a quantity defined as $\eta = \frac{4\epsilon E_p}{m_p^2 c^4}$, with ϵ the energy of the soft photons, $f_{ph}(\epsilon)$ is the energy distribution of the target soft photons, and $\Phi_i\left(\eta, \frac{E}{E_p}\right)$ is a function different for each output particle containing the information on the kinematics and the cross section of the interaction. Assuming $x = E/E_p$, its expression is

$$\Phi_i(\eta, x) = \begin{cases} B_i (\ln 2)^{\psi} & \text{if } x < x_- \\ B_i \exp\left\{-s_i \left[\ln\left(\frac{x}{x_-}\right)\right]^{\delta_i}\right\} \left[\ln\left(\frac{2}{1+y^2}\right)\right]^{\psi} & \text{if } x_- < x < x_+ \\ 0 & \text{if } x > x_+ \end{cases}, \tag{4}$$

where $y = \frac{x - x_-}{x_+ - x_-}$, and x_+, x_- define the maximum and minimum energies of each output particle. The index i indicates the type of output particle we are considering, which can be $\gamma-$rays coming from π^0 decay or leptons coming from $\pi^\pm$ decay. The parameters B_i, s_i and δ_i are functions of η depending on the type of particle considered, together with the parameter ψ.

In order to validate the implementation, we compared the results obtained using `agnpy` with the reference outputs shown in [11]. In particular, in Figs. 2, 3 we present the reproduction of Fig. 15 of the reference paper, showing the output spectra of $\gamma-$rays, electrons, positrons and neutrinos coming from the interaction between a power law distribution of protons with an exponential cutoff and the 2.7 K cosmic microwave background radiation. Table 2 reports the parameters used for the proton distribution, which were taken from [11]. Also in this case there is a good agreement between `agnpy` and the reference, being the deviation between the two results lower than 10%.

Table 2: Model parameters for the photo-meson process, taken from [11].

Parameter	value
$\gamma'_{p,min}$	1×10^{3}
$\gamma'_{p,cut}$	3.20×10^{11}
$\gamma'_{p,Max}$	1×10^{20}
α_p	2.0
k_p [cm^{-3}]	2.74×10^{-8}

PoS(ICRC2023)1524

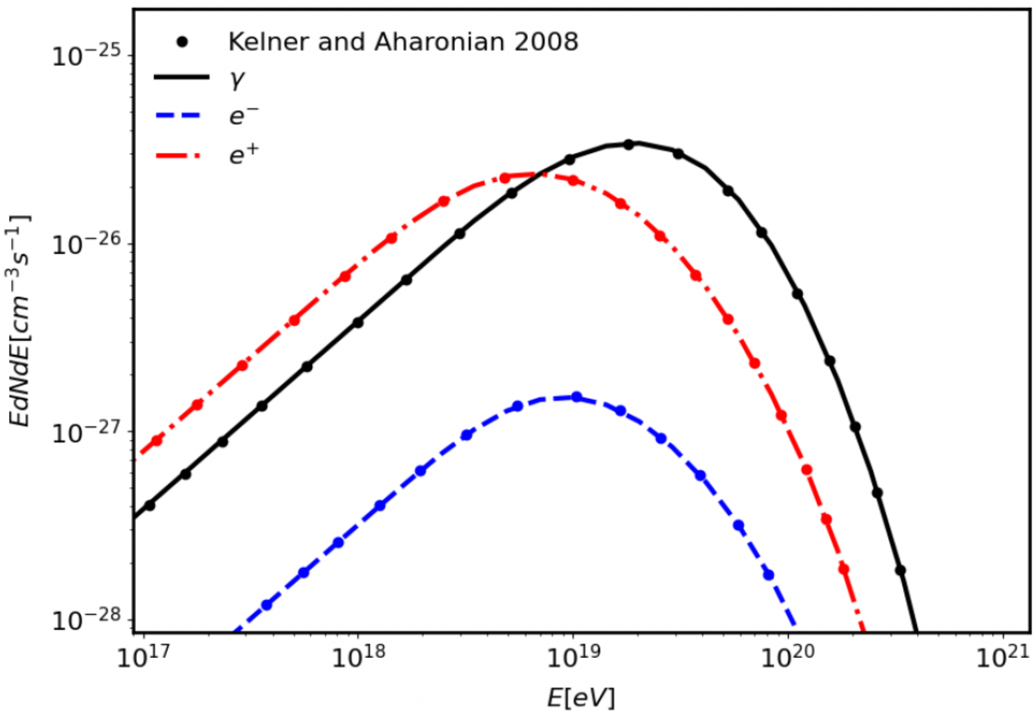

Figure 2: Spectra of output $\gamma-$rays (black solid line), electrons (blue dashed line), and positrons (red dashed dotted line).

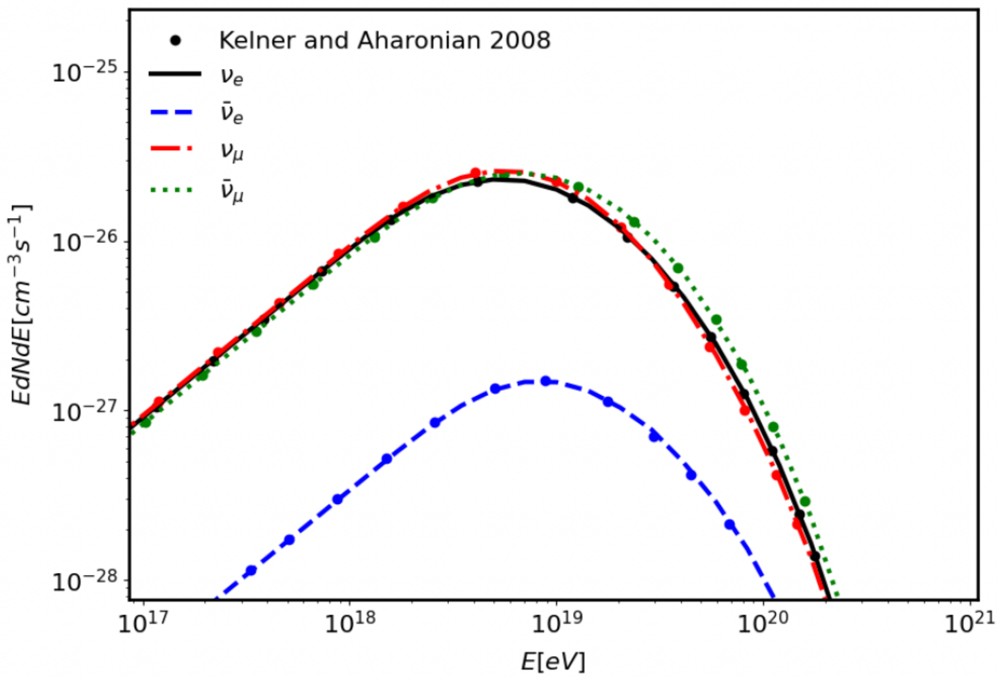

Figure 3: Spectra of output electron neutrinos (black solid line), electron antineutrinos (blue dashed line), muon neutrinos (red dashed dotted line), and muon antineutrinos (green dotted line).

4. Application

In Fig. 4 we show the code computing the SED due to synchrotron radiation from a blob containing a power-law distribution of electrons and a power-law distribution of protons. The result is shown in Fig. 5.

```
import numpy as np
import astropy.units as u
from astropy.constants import m_e, m_p
from agnpy.spectra import PowerLaw as PWL
from agnpy.emission_regions import Blob
from agnpy.synchrotron import Synchrotron
from agnpy.synchrotron import
ProtonSynchrotron
from agnpy.utils.plot import load_mpl_rc,
plot_sed
import matplotlib.pyplot as plt

load_mpl_rc()

# Emission region and radiative processes
n_e = PWL(k=2e-10 * u.Unit("cm-3"), p=2.8,  gamma_min=1e2, gamma_max=1e6, mass=m_e)
n_p = PWL(k=5e-8 * u.Unit("cm-3"), p=2.5,  gamma_min=10, gamma_max=1e11, mass=m_p)
blob = Blob(n_e = n_e, n_p=n_p)
esynch = Synchrotron(blob)
psynch = ProtonSynchrotron(blob)

# Compute the SED over an array of frequencies
nu = np.logspace(8, 29) * u.Hz
sed_esynch = esynch.sed_flux(nu)
sed_psynch = psynch.sed_flux(nu)

# Plot SED
plot_sed(nu, sed_esynch, label="electron synchrotron")
plot_sed(nu, sed_psynch, label="proton synchrotron")
plt.ylim([1e-30, 1e-25])
plt.show()
```

Figure 4: Example script to produce synchrotron emission from both electrons and protons.

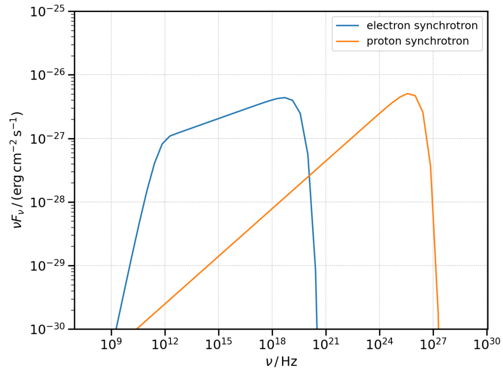

Figure 5: Output of the example script.

5. Conclusions and outlook

In this contribution we implemented the first hadronic processes in the open-source python package agnpy. The implemented processes are the synchrotron emission from relativistic protons, becoming relevant in case of high magnetic fields, and the photo-meson interactions, considered the primary source of neutrinos in AGNs and blazars emission. These processes are implemented following the analytical parametrizations of [10] and [11] respectively and the results obtained show a deviation of less than 10% in both cases if compared with the references, thus validating the code.

However, in order to have a more complete description of AGNs SED under a hadronic and lepto-hadronic point of view, other processes are required. In particular, proton-proton interactions become relevant when a dense target passes through the AGN jet, while the Bethe-Heitler pair production dominates over the photo-meson interactions at low energies. Moreover, the secondary particles created in all the cited processes undergo subsequent interactions giving origin to pair cascades, which can give a relevant contribution for example in the X-ray band (see e. g. [2]). The implementation of such processes is thus planned in order to let the user able to describe AGNs emission through lepto-hadronic processes in a more complete way.

This effort is made on an open-source software available to the astrophysical community in order to extend the possibility to perform modeling to the widest audience possible. This will become essential with the advent of the next generation high-energy observatories and the amount of data they will provide.

Aknowledgements

We would like to thank Matteo Cerruti for providing the results obtained with LeHa-Paris, allowing us to validate the new synchrotron process implemented in `agnpy`.

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