Hadronic modeling of AGN variability
Recent Progress

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HEPRO III
Long standing dispute between leptonic and hadronic models
Nowadays many non-HBL TeV sources have been observed
The need for hadronic models is evident
Variability allows a stricter determination of source parameters
Model setup

- Model consists of separate acceleration and radiation zone
- Acceleration of electrons and protons includes Fermi-I and Fermi-II
- Spectrum is derived self-consistently from jet microphysics

**Figure:** Geometrical structure of acceleration and radiation zone
Multizone models

Short detour: New model in development

- Spatially resolved model
- Shock is implemented as background fluid velocity
- Forward and backward moving electrons
- Particle flipping imitates small angle scattering
- Effectively Fermi-I

Please take a look at Stephan Richter’s poster for details. Hadronic radiation models will be implemented.

Figure: Geometry of the multizone model
General features

First proposed by Mannheim (1993)

- Nonthermal proton distribution
- \( p - \gamma \) photomeson production
- \( \pi^0 \)-decay into photons
- \( \pi^\pm \)-decay into \( e^\pm \) with subsequent synchrotron radiation
- Electron-positron-pairproduction

Figure: Hadronic fit for 3C279 (from Mannheim 1993)
Set of equations

Electron/Positron evolution

\[ \partial_t N_{e^{-}} = \partial_\gamma \left[ \left( \frac{\beta_{s,e} \gamma^2}{\text{Synchrotron}} + \frac{P_{\text{IC}}(\gamma)}{\text{Inverse Compton}} \right) \cdot N_{e^{-}} \right] \\
- \frac{N_{e^{-}}}{t_{\text{esc,e}}} + Q_{\text{pp}} + Q_{\text{p}^{-}} + Q \]

Proton evolution

\[ \partial_t N_p = \partial_\gamma \left[ \left( \frac{\beta_{s,p} \gamma^2}{\text{Synchrotron}} \right) \cdot N_p \right] - \frac{N_p}{t_{\text{rad,esc,p}}} + Q \]

Q is injected from the acceleration zone
Photon evolution

\[ \partial_t N_\gamma = R_S + R_C + R_{\pi^0} \]

- \( R_S \) Synchrotron
- \( R_C \) Inverse Compton
- \( R_{\pi^0} \) \( \pi^0 \) decay

\[ -c \left( \alpha_{SSA} + \alpha_{pp} \right) N_\gamma - \frac{N_\gamma}{t_{ph,esc}} \]

- \( \alpha_{SSA} \) Self synchrotron
- \( \alpha_{pp} \) Pairprod.

- \( t_{ph,esc} \) Escape
Hadronic implementation

- Previous models rely on Monte Carlo codes to simulate photomeson production
- The leading model here is the SOPHIA code (Mücke et al.) based on QGSJET
- Monte Carlo is not at any rate fast enough to produce time-dependent models
- One way out: Parametrization of results by Kelner & Aharonian

**Figure:** Parametric fit from Kelner & Aharonian
Hadronic fit - 3C279

Details: see Matthias Weidinger's poster
Hadronic fit - 3C279

Details: see Matthias Weidinger’s poster
Hadronic fit - 3C454.3

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Drawbacks of Kelner & Aharonian

- Unstable secondary particles are integrated out
- Implementation of new (accelerator) observations requires new Monte Carlo generator and new parametrization
Simplified Model

- New model design: More complete than delta
- Factorized response function
- Only single integration over the distribution function necessary
- Models some of the physical processes
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Simplified Model

\[ Q_{b}^{\text{IT}} = N_{p} \left( \frac{E_{b}}{\chi^{\text{IT}}} \right) \frac{m_{p}}{E_{b}} \int_{\epsilon_{\text{th}}/2}^{\infty} dy \; n_{\gamma} \left( \frac{m_{p} y \chi^{\text{IT}}}{E_{b}} \right) M_{b}^{\text{IT}} f^{\text{IT}}(y) \]

\[ R_{b}(x, y) \equiv \sum_{\text{IT}} R^{\text{IT}}(x, y) \equiv \sum_{\text{IT}} \frac{1}{2y^{2}} \int_{\epsilon_{\text{th}}}^{2y} d\epsilon_{r} \epsilon_{r} \sigma^{\text{IT}}(\epsilon_{r}) M_{b}^{\text{IT}}(\epsilon_{r}) \delta \left( x - \chi^{\text{IT}}(\epsilon_{r}) \right). \]

factorizes in

\[ R^{\text{IT}}(x, y) = \delta(x - \chi^{\text{IT}}) M_{b}^{\text{IT}} f^{\text{IT}}(y) \]

with

\[ f^{\text{IT}}(y) \equiv \frac{1}{2y^{2}} \int_{\epsilon_{\text{th}}}^{2y} d\epsilon_{r} \epsilon_{r} \sigma^{\text{IT}}(\epsilon_{r}). \]
Simplified Model

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\[ Q_b(E_b) = \int_{E_b}^{\infty} \frac{dE_p}{E_p} N_p(E_p) \int_{\epsilon_{th}}^{\infty} d\epsilon n_\gamma(\epsilon) R_b(x, y) \]
Pion production in the AGN testcase
New model allows also for the prediction of neutrino flux

Neutrino-/Anti-Neutrino-Production rate
Neutrino Emission

GRB: $\nu_e/\bar{\nu}_e$

AGN: $\nu_e/\bar{\nu}_e$

BB: $\nu_e/\bar{\nu}_e$

GRB: $\nu_\mu/\bar{\nu}_\mu$

AGN: $\nu_\mu/\bar{\nu}_\mu$

BB: $\nu_\mu/\bar{\nu}_\mu$

Neutrino-/Anti-Neutrino-Production rate

Felix Spanier (Uni Würzburg)
Better prediction of neutrino flavor

Flavor-ratio for $\mu$-e-Neutrinos
Summary

- Time-dependent lepto-hadronic model including particle acceleration is available
- Complicated time variation patterns
- New photo-meson production model is discussed