ExHaLe-jet:
An extended hadro-leptonic jet model for blazars

Michael Zacharias,
Anita Reimer, Catherine Boisson, Andreas Zech

Landessternwarte, Universität Heidelberg, Heidelberg, Germany
Centre for Space Research, North-West University Potchefstroom, South Africa

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Introduction

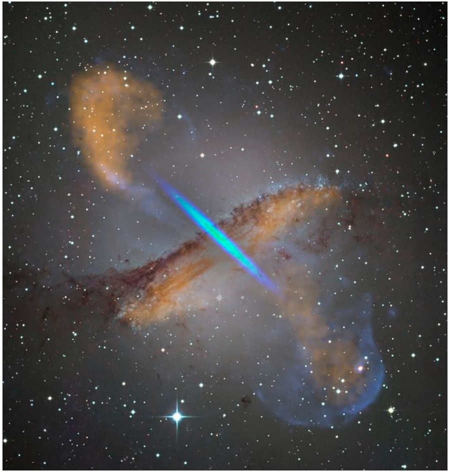


Figure 1: MWL image of Centaurus A with H.E.S.S. emission overlaid HESS+20

- Blazars are well described through the one-zone model
- Noteworthy counter-examples are:
  - AP Librae Hervet+15, Sanchez+16, MZ&Wagner16, Roychowdhury+22
  - Centaurus A HESS+20
- Need for extended, kinetic jet models

  Potter&Cotter12,13, Zdziarski+14, Lucchini+19, . . .

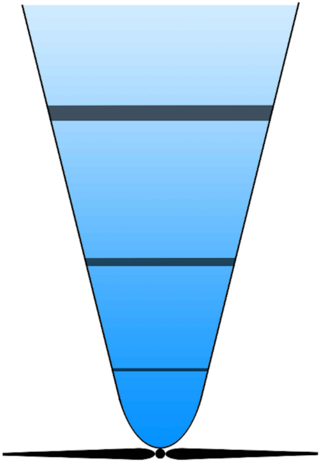


Figure 2: Sketch: jet cut into numerous slices (dark), in which the kinetic equations for each particle species are solved Figure: courtesy of Jonathan Heil

An **Ex**tended **Ha**dro-**Le**ptonic jet model

- Jet length cut into numerous slices, where kinetic equation is solved for each species
  - Injection of primary proton and electron distribution at the base; evolved self-consistently along the jet
  - Injection of secondaries (pions, muons, pairs) in each slice
  - Pairs propagated along with primaries
  - Radiation and neutrino output for each slice
- Geometry currently fixed as
  - Parabolic acceleration region: $\Gamma_b(z) \propto \sqrt{z}$
  - Conical coasting region $\Gamma_b(z) =$const.
  - Radius: $R(z) \propto \tan\left[0.26/\Gamma_b(z)\right]$
  - Magnetic field derived with Bernoulli equation
- Considered radiation processes & fields
  - Synchrotron, photomeson production, $e^{+/-}$-inverse-Compton
  - Accretion Disk, BLR, DT, CMB
  - BLR and DT depend on Accretion Disk

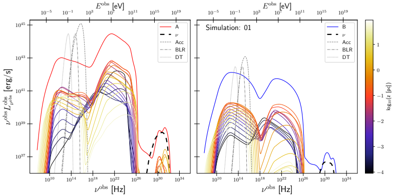


Figure 3: Total spectrum (observer's frame) with distance evolution (color code) for strong (left) and weak (right) accretion disk. Thick dashed lines marks the muon-neutrino spectrum.

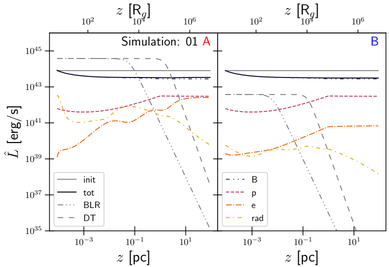


Figure 4: Luminosities (observer's frame) over distance for a strong (left) and weak (right) accretion disk.

- Length scales:
  - $z_{max} = 100$pc, $z_{acc} = 1$pc
  - $R_{BLR} \sim 0.05$pc (strong), ~ 0.005pc (weak)
  - $R_{DT} \sim 1$pc (strong), ~ 0.1pc (weak)
- Photon spectrum dominated by leptonic processes (synchrotron, external Compton)
- Strongest contribution around 0.1–1 z_{acc}
- External fields have strong impact (*left*: strong disk, *right*: weak disk)
  - "Compton dominance"
  - p-γ interactions (cf. π^0 bump)
  - Neutrino spectra
- Total jet power sub-Eddington
- Jet power dominated by magnetic field (initial value $B(0) = 50$G)

ExHaLe-jet: Solution without external fields

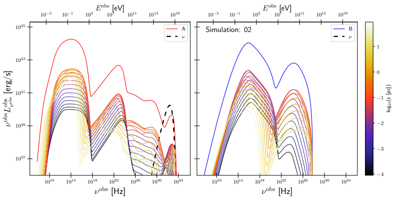


Figure 5: Total spectrum (observer's frame) with distance evolution (color code) for the p-synchrotron (left) and SSC (right) case. Thick dashed line marks the muon-neutrino spectrum.

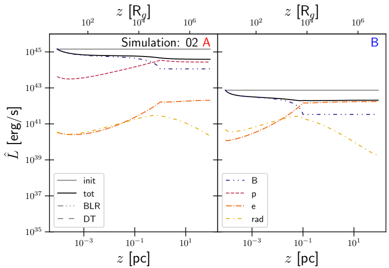


Figure 6: Luminosities (observer's frame) over distance for the p-synchrotron (left) and SSC (right) case.

- Length scales:
  - $z_{max} = 100$pc
  - $z_{acc} = 1$pc (left), $z_{acc} = 0.1$pc (right)
- Proton synchrotron (left):
  - Protons contribute around 0.01–0.3 z_{acc}
  - Electrons contribute around 0.05–10 z_{acc}
  - Protons dominate luminosity after 1 z_{acc}
  - Neutrinos still too weak
- Pure SSC case (right):
  - Peak contribution around 1 z_{acc}
  - Electrons dominate luminosity after 1 z_{acc}

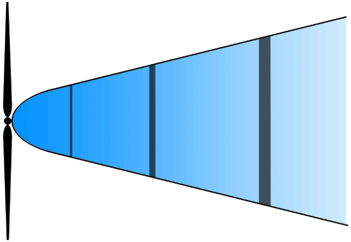


Figure 7: Sketch: jet cut into numerous slices (dark), in which the kinetic equations for each particle species are solved Figure: courtesy of Jonathan Heil

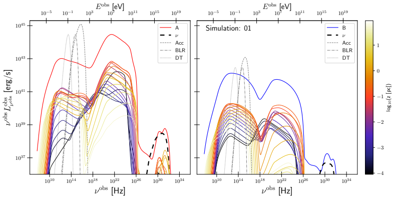


Figure 8: Total spectrum (observer's frame) with distance evolution (color code) for strong (left) and weak (right) accretion disk. Thick dashed line marks the muon-neutrino spectrum.

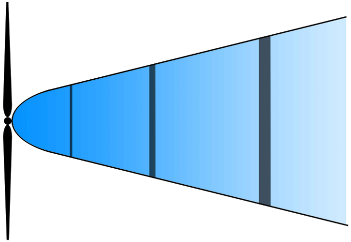
An **Ex**tended **Ha**dro-**Le**ptonic jet model

- Flexible, kinetic, hadro-leptonic code to model the emission from an extended jet
- Parameter set results in a leptonic dominance in the spectrum
- Influence of protons (secondaries, neutrinos, etc) important

Outlook:

- Code enhancements (neutrons, details of particle transport, specific acceleration zones, etc)
- Source modeling

Summary



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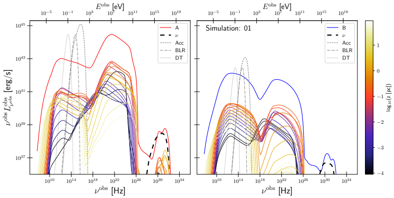

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All details: Zacharias+22, arXiv:2203.07956

Thank you!

Processes considered in the code

$$\frac{\partial n_i(\chi,t)}{\partial t} = \frac{\partial}{\partial \chi}\left[\frac{\chi^2}{(a+2)t_{\rm acc}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right] - \frac{\partial}{\partial \chi}\left(\dot{\chi}_i n_i(\chi,t)\right) + Q_i(\chi) - \frac{n_i(\chi,t)}{t_{\rm esc}} - \frac{n_i(\chi,t)}{\gamma t^*_{i,\rm decay}}$$

$(\chi = \gamma\beta)$

Cooling processes:

- Protons: synchrotron, adiabatic, p-γ, Bethe-Heitler
- Charged pions / muons: synchrotron, adiabatic
- Electrons: synchrotron, adiabatic, inverse Compton

Acceleration processes:

- Fermi I/II, but only as a “re-acceleration”
- Main acceleration through a generic injection term

Photon absorption processes:

- Pair production on all photon fields (external ones angle averaged in the comoving frame after boosting)
- Synchrotron-self absorption
- Photons that left the emission region, are also absorbed in the BLR and DT fields (but no EBL or CMB absorption considered)

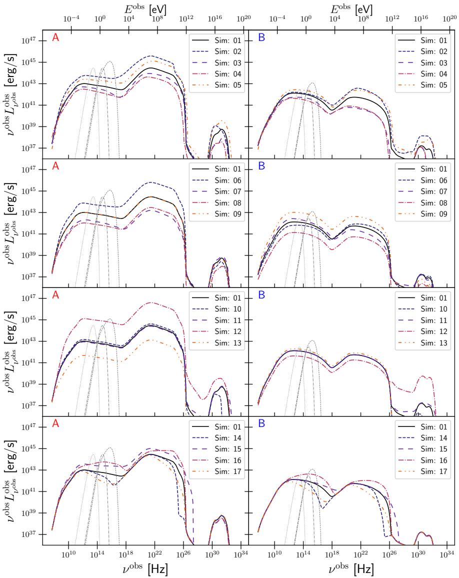

Figure 9: Parameter scan

- Parameter study based on simulation 01 (with external fields)
- Parameter details in arXiv:2203.07956
- Especially a hard proton distribution (sim12), a short acceleration region (sim02), and a small initial magnetic field (sim06) enhance the luminosity
- . . . but only for strong external fields! In weak fields, effects are less pronounced.
- The reason is that these changes enhance the development of the secondray cascade, i.e. more pairs and thus more

Table 1: Parameters and values of the simulation with external fields

Parameter	Value	Parameter	Value
Redshift	0.5		
Black hole mass	$3.0 \times 10^8\, M_\odot$	Initial magnetic field	50 G
Eddington ratio	A: 10^{-1}	Frac injected power [$L_{\rm edd}$]	3.0×10^{-6}
	B: 10^{-3}	Initial proton to electron ratio	1
BLR temperature	10^4 K	Minimum proton Lorentz factor	2
DT temperature	5.0×10^2 K	Maximum proton Lorentz factor	2×10^8
Jet length	100 pc	Proton spectral index	2.5
Acceleration region	1 pc	Minimum electron Lorentz factor	100
Max jet Lorentz factor	30.0	Maximum electron Lorentz factor	1×10^5
Jet viewing angle	$1.9^{\rm o}$	Electron spectral index	2.5
Frac Jet opening angle	0.26		
Frac Initial jet width	10.0		
Frac Escape time scale	10.0		
Frac Acceleration time scale	10.0		

Table 2: Parameters and values of the simulation without external fields (proton synchrotron, pure SSC)

Parameter	Value	Parameter	Value
Redshift	A: 0.5, B: 0.2	Initial proton to electron ratio	A: 1, B: 10^{-10}
Black hole mass	$3.0 \times 10^8\, M_\odot$	Min proton Lorentz factor	2
Eddington ratio	10^{-4}	Max proton Lorentz factor	A: 2×10^{10}
Jet length [pc]	100		B: 200
Acceleration region [pc]	A: 1, B: 0.1	Proton spectral index	A: 2.0, B: 2.8
Max jet Lorentz factor	A: 50, B: 30	Min electron Lorentz factor	A: 100
Jet viewing angle	A: 1.15°, B: 1.9°		B: 10^4
Frac Jet opening angle	0.26	Max electron Lorentz factor	A: 2×10^4
Frac Initial jet width	A: 30, B: 5		B: 2×10^6
Frac Escape time scale	10.0	Electron spectral index	A: 2.0, B: 2.8
Frac Accel. time scale	10.0		
Initial magnetic field [G]	A: 70, B: 30		
Frac injected power [$L_{\rm edd}$]	A: 2.0×10^{-4}		
	B: 2.0×10^{-6}		